04 Ecology

Essential ideas

4.1 The continued survival of living organisms, including humans, depends on sustainable communities

4.2 Ecosystems require a continuous supply of energy to fuel life processes and to replace energy lost as heat.

4.3 Continued availability of carbon in ecosystems depends on carbon cycling.

4.4 Concentrations of gases in the atmosphere affect climates experienced at Earth's surface.

This colourful vegetation and blue sky are a stark contrast to what we would see on the surface of our inhospitable neighbours, the Moon, Mars, or Venus. Our planet shows complex interactions between the atmosphere, water, and living organisms.

Could you live on the Moon or on another planet such as Mars? If you had to make a list of what you would need, there would be some obvious things, such as liquid water, food, and oxygen gas to breathe. But is it possible to maintain life for a long period of time outside established ecosystems?

For example, if you brought bottles of oxygen gas with you to breathe, eventually they would run out. What could you bring with you that could supply oxygen regularly? The same questions can be asked about food and water.

A group of researchers tried such an experiment here on Earth by building a sealed living space called Biosphere II in the desert of Arizona, complete with a rainforest, a miniature ocean, land for growing food, and livestock to provide eggs and milk. A small group of people lived inside for 2 years in the early 1990s, and they learnt a great deal about sustaining life in a closed system. Such an experiment helps us to learn how we might set up a base on the Moon or perhaps Mars but, more importantly, it helped the people living inside appreciate what a delicate balance there is between air, water, and life: a balance that is complex and can be disrupted by actions with unintended consequences.

4.1 Species, communities, and ecosystems

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Looking for patterns, trends, and discrepancies: plants and algae are mostly autotrophic but some are not.

Understandings:

- Species are groups of organisms that can potentially interbreed to produce fertile offspring.
- Members of a species may be reproductively isolated in separate populations.
- Species have either an autotrophic or heterotrophic method of nutrition (a few species have both methods).
- Consumers are heterotrophs that feed on living organisms by ingestion.
- Detritivores are heterotrophs that obtain organic nutrients from detritus by internal digestion.
- Saprotrophs are heterotrophs that obtain organic nutrients from dead organisms by external digestion.
- A community is formed by populations of different species living together and interacting with each other.
- A community forms an ecosystem by its interactions with the abiotic environment.
- Autotrophs obtain inorganic nutrients from the abiotic environment.
- The supply of inorganic nutrients is maintained by nutrient cycling.
- Ecosystems have the potential to be sustainable over long periods of time.

Applications and skills:

- Skill: Classifying species as autotrophs, consumers, detritivores, or saprotrophs from a knowledge of their mode of nutrition.
- Skill: Setting up sealed mesocosms to try to establish sustainability.
- Skill: Testing for association between two species using the chi-squared test with data obtained by quadrat sampling.
- Skill: Recognizing and interpreting statistical significance.

Guidance

- *Mesocosms can be set up in open tanks, but sealed glass vessels are preferable because entry and exit of matter can be prevented but light can enter and heat can leave. Aquatic systems are likely to be more successful than terrestrial ones.*
- *To obtain data for the chi-squared test, an ecosystem should be chosen in which one or more factors affecting the distribution of the chosen species varies. Sampling should be based on random numbers. In each quadrat the presence or absence of the chosen species should be recorded.*

The interdependence of living organisms

In 1980 there was a major volcanic catastrophe at Mount Saint Helens on the west coast of the USA. After the massive eruption, little was left of the forest and rivers that had existed on and around the mountain. The blast from the eruption knocked over massive adult trees as if they were straws.

Forest fires and hot gases burned everything in sight. Volcanic ash rained down, smothering the destroyed forest and covering the carcasses of the animals that died there. Many species that could escape fled the area. Although thousands of people were evacuated, a few did die that day; some of those who died were photographers trying to get the photo of a lifetime.

Yet, within months of the eradication of the ecosystem, life was back. Seeds, dropped by birds or blown in by the wind, germinated in the fertile volcanic ash. Little by little, insects, then birds, then small mammals, moved in. Within a couple of decades, a grassland and shrub ecosystem had reappeared. Today, thousands of species flourish in what had been a desolate landscape.

These trees were knocked down by the Mount Saint Helens eruption in 1980. The ecosystems on the mountain were destroyed.

What is a species?

The definition of a species is a group of organisms that can interbreed and produce fertile offspring. Members of the same species have a common gene pool (i.e. a common genetic background).

This giant panda has characteristics that set its species apart; it cannot breed with other species that are not giant pandas.

Species is the basic unit for classifying organisms. It is one of those words everyone thinks they know, but it is not an easy concept. A species is made up of organisms that:

- have similar physiological and morphological characteristics that can be observed and measured
- have the ability to interbreed to produce fertile offspring
- are genetically distinct from other species
- have a common phylogeny (family tree).

There are challenges to this definition, however. Sometimes, members of separate but similar species mate and succeed in producing hybrid offspring. For example, a horse and a zebra, or a donkey and a zebra, can mate and produce offspring that are called zebroids. In these examples, the parents are both equines (they belong to the horse family, Equidae), so they are related, but they are certainly not the same species. They do not possess the same number of chromosomes, which is one of the reasons why the hybrid offspring produced are usually infertile.

Other challenges to our definition of species include the following.

- What about two populations that could potentially interbreed, but do not because they are living in different niches or are separated by a long distance?
- How should we classify populations that do not interbreed because they reproduce asexually? (The definition above is clearly aimed at sexually reproducing organisms, and cannot be applied to bacteria or archaeans.)
- What about infertile individuals? Does the fact that a couple cannot have a child exclude them from the species? What about the technique of *in vitro* fertilization? What challenges does that pose to the definition of species?

The answers to these questions are beyond the scope of this book and the IB programme. However, you should always think critically about any definition: at first glance it may appear to be straightforward, but on closer scrutiny it can be cause for debate.

All domestic dogs are the same species

Domesticated dogs are all the same species: *Canis familiaris*. In theory, that means that any two dogs from anywhere in the world can mate and have puppies that will grow up and be able to mate with any other dogs, and have more puppies.

Hybrids

To understand the idea of fertile offspring, think about what happens when two different but similar species mate and produce offspring. For example, a female horse and a male donkey can mate and produce a mule. However, mules cannot usually mate to make more mules. Because the offspring (the mules) are not fertile, no new species has been created. Instead, a mule is called an interspecific hybrid. When a male lion and a female tiger are crossed, a liger is the name of the hybrid formed.

Hybrids face several challenges to continue as a population. For one thing, the vast majority of animal and plant hybrids are infertile. Even if one generation of hybrids is produced, a second generation is highly unlikely. This presents a genetic barrier between species.

Some examples of animal hybrids are:

- female horse + male donkey = mule
- female horse + male zebra = zorse
- female tiger + male lion = liger.

A liger is a hybrid between a lion and a tiger, and is considerably larger than either parent animal.

Populations can become isolated

If a group from a species is separated from the rest of the species, it might find itself evolving in a different way compared with the rest of the population. For example, mice have inadvertently crossed oceans after going on board ships looking for food, and found themselves hundreds if not thousands of kilometres away from where their parent population lived, perhaps on an island far from any mainland. Two or more mice can mate and have litters of mice that then form a new population on the island. This new population is reproductively isolated from the original population of mice. Compared with the original population on the mainland, an island population of mice may end up with different frequencies of certain alleles for a trait such as fur colour, with the result that the mice in the island population only have black fur, while the mice in the original mainland population can have either brown or black fur.

As well as bodies of water, there are other ways in which populations of the same species can be isolated from each other, such as mountain ranges or deep canyons. There are tree snails in Hawaii, for example, that are present on one side of a volcanic mountain but not the other. But physical objects are not always responsible for separating populations of a species. Think of a group of birds that migrate: if some of those birds arrive early in the springtime and start nesting before the others arrive, the early birds' genes will be isolated from the birds that arrive and nest later. If some birds in a population develop a mating call that is different from the others, this could also potentially separate one population into two groups: one that likes the old call and one that likes the new call. Over time, this might lead to speciation: a new species is formed from an old one. You will find out more about isolation and speciation in Section 10.3.

Autotrophs and heterotrophs

A sheep eating grass is an example of a heterotroph (the sheep) feeding on an autotroph (the grass).

Autotrophs

Some organisms are capable of making their own organic molecules as a source of food. These organisms are called autotrophs, and they synthesize their organic molecules from simple inorganic substances. This process involves photosynthesis. In other words, autotrophs can take light energy from the Sun, combine it with inorganic substances, and obtain a source of chemical energy in the form of organic compounds. Because autotrophs make food that is often used by other organisms, they are called producers.

Examples of autotrophs include:

- cyanobacteria
- algae
- grass
- trees.

Heterotrophs

Heterotrophs cannot make their own food from inorganic matter, and must obtain organic molecules from other organisms. They get their chemical energy from autotrophs or other heterotrophs. Because heterotrophs rely on other organisms for food, they are called consumers. Heterotrophs ingest organic matter that is living or has been recently killed.

Examples of heterotrophs include:

- zooplankton
- fish
- sheep
- insects.

Consumers

Organisms that are not capable of synthesizing their own food from inorganic components of their environment need to get their nourishment by ingesting (eating) other organisms. For example, humans are heterotrophs: we cannot simply lie out in sunlight to get our food the way phytoplankton and plants can. We are consumers: we need to eat other living organisms, whether they are products of autotrophs, such as fruits and vegetables, or products of heterotrophs, such as meat, eggs, honey and dairy products. Consumers take the energy-rich carbon compounds, such as sugars,

CHALLENGE YOURSELF

1 From the photo, identify the following:
  (a) non-living inorganic components, both visible and non-visible (these are referred to as abiotic components)
  (b) living components, both visible and non-visible (living organisms are referred to as biotic components)
  (c) autotrophs present, both visible and non-visible
  (d) heterotrophs present, both visible and non-visible.

Can you identify the biotic and abiotic components in this photo?

proteins, and lipids, synthesized by other organisms in order to survive. The only component in our diet that we can synthesize, by exposure to sunlight, is vitamin D. There are precursors in human skin that absorb ultraviolet (UV) light waves and produce vitamin D. But in order to get all the other types of molecules needed to keep us healthy, we need to consume other living things.

The minotaur beetle, *Typhaeus typhoeus*, is a detritivore.

Detritivores

Some organisms eat non-living organic matter. Detritivores eat dead leaves, faeces, and carcasses. Earthworms, woodlice, and dung beetles are detritivores found in the soil community. Many, but not all, bottom feeders in rivers, lakes, and oceans are detritivores.

Saprotrophs

Organisms called saprotrophs live on or in non-living organic matter, secreting digestive enzymes and absorbing the products of digestion. Saprotrophs play an important role in the decay of dead organic materials. The fungi and bacteria that are saprotrophs

are also called decomposers, because their role is to break down waste material. A mushroom growing on a fallen tree is secreting enzymes into the dead tissue of the tree trunk, in order to break down the complex molecules within the tree tissue, and then the mushroom absorbs the simpler energy-rich carbon compounds that are released by the action of the enzymes. Slowly, over time, the tree trunk decomposes as the molecules inside the wood are liberated and reused.

Fungi are saprotrophs. Although edible mushrooms are found in the fruit and vegetable section of your local supermarket, they are not classified by biologists as plants. It is arguable that they should be with other consumers in the meat section.

Communities

A community is a group of populations living and interacting with each other in an area. Examples include the soil community in a forest and the fish community in a river.

In ecology, the term 'interacting' can mean one population feeding on another, or being eaten. It can mean that one species provides vital substances for another, as in the case of symbiotic bacteria, which help certain plants get nitrogen while the bacteria grow in the plant root nodules. It can also mean that one species gets protection from another, as in the case of aphids being protected by ants from attacks by predators. Interacting can mean that one species relies on another for its habitat, as is the case for parasites living on or inside the bodies of other animals.

CHALLENGE YOURSELF

2 From Figure 4.1, pick three organisms and determine how many other organisms each one depends on. Which organisms depend on them? What about environmental factors? Which ones does each organism contribute to, and which ones does each depend on?

Figure 4.1 A tropical rainforest contains many interactions between living organisms and their environment.

NATURE OF SCIENCE

Classification is all about looking for patterns and grouping organisms together according to those patterns. This can be challenging when looking at algae. Because they are green and photosynthesize, organisms such as seaweed used to be considered to be plants, until closer examination revealed that they do not possess the structures we expect to find in plants, such as roots and leaves. Today seaweed is classified as algae. Classifying all algae as autotrophs is also a challenge, because some species live as parasites and do not actually use their photosynthetic capabilities.

Ecosystems

The term abiotic refers to components of the environment that are non-living, such as water, air, and rocks. When abiotic measurements are taken of an environment, they can include temperature, pH, light levels, and the relative humidity of the air. Such things are often measured using electronic probes and data-logging techniques. Although these factors are not living entities, they are often of great interest to biologists because of the interactions that living things have with them. Temperature and humidity, for example, have a large influence on the types of plant life found in a community; an open marsh will not have the same kinds of plants as a dense forest. To find out to what extent a particular abiotic factor influences a species' distribution, many measurements must be taken, of both the abiotic and biotic (living) aspects of the environment. One technique used to determine the frequency and distribution of a species is random sampling.

An example of an easily identifiable plant to use for the fieldwork lab; in this case the plant is yarrow.

Fieldwork

To understand random sampling, try this lab using quadrats. A quadrat is a square of a particular dimension that can be made of a rigid material such as metal, plastic, or wood. In this example, each group will use a 1-m^2 quadrat. Other materials you will need are: a table of random numbers from 1 to 99, a pencil, and something on which to record your data.

- Pick a well-defined area, such as a fenced-in pasture, public park, or a sports field with natural grass (be sure you have permission to work there first).
- Choose a species of plant that grows there that is easy to identify and that is widespread throughout the area, but not so numerous that counting the number of individuals growing in a square metre would take more than a minute or two. Possible examples are dandelions, docks, and yarrow, but the choice will depend on where you live and when you carry out the lab.
- Each group should start in a different part of the area and spin a pencil to determine a random direction. Then, with your group, look at the first number on the random number table and walk in the designated direction that number of steps. If the border of the area is reached before the designated number of steps has been taken, you should 'bounce' off the border like a ray of light off a mirror, and continue in the direction dictated by an angle of incidence that is the same as the angle of reflection.
- Place the quadrat down on the ground at the point determined by the number of steps, and decide which of the four sides will be the 'top' and 'right' of the quadrat.
- Identify and count the number of individuals of the chosen species found inside the borders of the quadrat at that position. If it is zero, record the result as such. Any plants touching the top or right should be considered 'in' and should be counted. Any plants touching the bottom or left side of the quadrat should be considered 'out' and not counted.
- Repeat this as many times as possible in, say, an hour: the more quadrats, the better. However, a typical sports field might be 5000 m^2, so there is no way a group can sample all 5000 m^2 and cover the entire field: that is why random sampling is used.
- Before leaving the area you are working in, measure its dimensions so that its total surface area can be determined. This might be challenging for an irregularly shaped pasture or park, in which case online aerial views of the area might be useful. In that case, note the scale of the image.
- Now you will carry out some data processing. Determine how many plants you hit per square metre, then use the surface area calculation to estimate the total number of individuals of that plant that are living in that area: (plants per m^2) × (surface area in m^2) = (population estimation).

If this experiment is done for two species of plants, are there any calculations you could do to compare the two? See the Mathematics, and information and communication chapter for more about statistical tests.

Alternative: if weather or space forces a group to do this indoors, the activity can be simulated with disks of paper or sticky notes scattered around a gymnasium. In such a case, use a smaller quadrat, maybe one that is 50 cm^2. An advantage of this alternative lab is that the person scattering the disks or sticky notes knows how many there are in total, and it is interesting to see how close the groups' estimations are to the known number.

Systematic sampling techniques

There is another way of using a quadrat rather than the random sampling described in the lab above: systematic sampling using a transect. A transect is a line traced from one environment to another, such as from a grassland into a woodland, or from an ocean's intertidal zone over dunes. The line might be 10, 25, or 50 m long, and can be made using a long tape measure or piece of string or rope. This method involves laying down a quadrat either every metre along the transect, or at specific intervals along the transect, for example every 2 m, 5 m, or 10 m, and then counting the organisms that hit each quadrat and then counting the organisms found within each quadrat. Notice how, unlike the example of the quadrats used in the fieldwork lab, there are no random numbers. Because the distances are measured carefully, this is especially interesting in cases where we want to see if there is a relationship between the distribution of organisms that live along the transect and an abiotic factor that changes along the transect, such as temperature, humidity, and light levels.

Worked example

Let's suppose a group of students has been working in a forest in late summer and they have measured several abiotic factors, including light intensity in two distinct areas: a heavily wooded area and an open prairie. Not surprisingly, they recorded major differences in light intensity between one area and the next. They identified a particular species of fern that grows in both areas but appears to prefer shaded areas compared with areas exposed to direct sunlight. After collecting their data, they wanted to see if the presence of ferns was statistically significantly larger in the shaded areas (the woodland) compared with the areas in direct sunlight (the prairie). The group was divided into two teams: one for the woodland and the other for the prairie. They used random sampling with 1-m^2 quadrats to get their data. If they found the fern growing in their quadrat, they recorded a 1, if not, a 0. Table 4.1 shows what their data looked like after 20 quadrats had been thrown by each group.

Quadrat	Shade (woodland)	Sunlight (prairie)	Quadrat	Shade (woodland)	Sunlight (prairie)
1	0	1	11	1	0
2	1	1	12	1	0
3	1	0	13	0	0
4	1	0	14	1	1
5	1	0	15	0	0
6	0	1	16	1	1
7	1	0	17	1	1
8	1	1	18	1	0
9	0	0	19	0	0
10	1	0	20	1	0

Table 4.1 Quadrat data for a fern species. Legend: 1=presence of ferns in quadrat, 0=absence of ferns in quadrat

Apply the chi-squared test to these data to decide whether the shade had an influence or not on the distribution of the fern. (See page 797 for an explanation of what the chi-squared test is, how it works, and what the values for the degrees of freedom should be.)

1 State the null hypothesis in this calculation.
2 Determine the number of degrees of freedom in this calculation.
3 Determine the critical value in order to obtain a 95% certainty that there is a statistically significant difference between these two sets of numbers.
4 Calculate the chi-squared value for these data.
5 Interpret this value. Does it mean we can accept or reject the null hypothesis?
6 Is there a statistically significant difference between these two sets of data?
7 Are there enough data to be confident of the results?

Solutions

1 The null hypothesis is 'the two categories (presence of fern and presence of shade) are independent of each other'. In other words, the distribution of this fern species is not related to shade.
2 Because there are two possible outcomes (fern present or fern not present), the number of degrees of freedom is 2 – 1 = 1.
3 According to the chi-squared table (see Table 5 on page 796), the critical value in order to obtain a 95% certainty is 3.84. This value is found under the column 0.05, which corresponds to a 95% certainty, and it is found in the row that has the degree of freedom of 1.
4 The chi-squared value is calculated to be 4.91. This is obtained using the following values in the contingency tables.

Table 4.2 The table of observed values

	Shade (woodland)	Sun (prairie)	Grand total
Fern absent	6	13	19
Fern present	14	7	21
Grand total	20	20	40

Below, the expected value of 9.5 is from the calculation: (20 × 19) ÷ 40 and the expected value of 10.5 is from the calculation (20 × 21) ÷ 40.

Table 4.3 The table of expected values

	Shade (woodland)	Sun (prairie)	Grand total
Fern absent	9.5	9.5	19
Fern present	10.5	10.5	21
Grand total	20	20	40

See page 797 of the Mathematics, and information and communication chapter for help with this calculation.

5 Because 4.91 is greater than the critical value of 3.84, this means we can rej ect the null hypothesis.
6 Yes, the two categories are related to each other. We can be 95% sure that there is a relationship between the fern distribution and amount of sunlight. In other words, it would be very unlikely that they are independent of each other.
7 Twenty quadrats sounds a bit small. In a random sample, there is always the chance that the sampling is not representative of the zone studied. If the zone in the sunlight was the size of a sports field, for example, it would have a surface area of approximately 5000 m^2. Twenty 1-m^2 quadrats represents 20 m^2 of that surface, meaning that only 0.4% of the field was actually sampled. The same can be said for the shaded area in the woods.

You can be asked about the chi-square test in IB biology exams. Be sure you know when the chi-square test can be used, the steps of how to do it, and how to interpret the results.

Where do autotrophs get their nutrients?

Unlike consumers, who need to eat organic food from plants and animals, autotrophs can make the food they need from their inorganic surroundings. Photosynthetic organisms, such as phytoplankton, cyanobacteria, and plants, are able to produce food by using carbon dioxide, water, and sunlight. They make food from air using sunlight energy. It is a truly remarkable process, and no consumers could survive on this planet without the initial production of food by autotrophs. Because of this ability to make food from inorganic substances, autotrophs are referred to as producers, and they are the start of food chains, which will be explored later in Section 4.2.

Long before plants evolved on Earth, cyanobacteria were photosynthesizing. Cyanobacteria have been producers for many ecosystems.

Earth has various systems that interact.

Biosphere = where all living things are found.

Atmosphere = where all the gases in the air are found.

Lithosphere = where all the rocks are found.

Hydrosphere = where all the water is found.

Each one of these systems is closely linked with the others, and some, such as the biosphere, cannot exist in their current form without the other three.

Nutrient cycling

When organisms such as trees need minerals to grow and stay healthy, where do they get them from? Even though tonnes of space dust fall on Earth each year, there is not enough to meet the mineral needs of all the organisms in the biosphere. As a result, ecosystems must recycle the carbon, nitrogen, and other elements and compounds necessary for life to exist. For this, organisms must find what they need within the materials available in their own habitat. The problem is that organisms absorb valuable minerals and organic compounds and use them to build their cells. These resources are then locked up and unavailable to others, except, of course, through feeding and decomposition.

Decomposers

An effective way to unlock the precious nutrients stored in the cells of plants and animals is through decay. Decomposers (saprotrophs and detritivores) break down the body parts of dead organisms. The digestive enzymes of decomposers convert the organic matter into a more usable form for themselves and for other organisms. For example, proteins from a dead organism are broken down into ammonia (NH_3) and, in turn, ammonia can have its nitrogen converted into useful nitrates (NO_3^-) by bacteria.

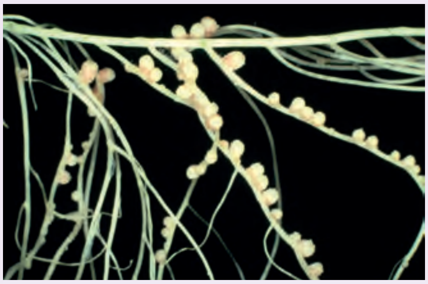
In this way, decomposers recycle nutrients so that they are available to other organisms and are not locked inside the bodies or waste products of organisms in the ecosystem. Decomposers play a major role in the formation of soil, without which plant growth would be greatly impaired, if not impossible. The rich black layer of soil called humus is made up of organic debris and nutrients released by decomposers. In a vegetable garden, a compost pile is used to convert plant waste from the garden and kitchen into rich humus that can then be used to grow new vegetables. The organisms doing the work inside the compost pile are decomposers.

When talking about the health of Planet Earth, we often use words like 'pollution' and 'waste'. Ecologists studying ecosystems noticed very quickly that what one organism considers to be waste is what another organism considers to be a valuable resource. For example, the nitrogen compounds found in rotting flesh or animal excrement are extremely useful for plant growth. In other words, 'pollution' can be considered to be simply misplaced resources. If we can figure out a system that makes waste useful, then it will be a sustainable system, and all the waste will be put to a new use as part of a cycle. If we cannot find a use for the waste we produce, then we truly are polluting our environment.

CHALLENGE YOURSELF

3 For each organism below, identify which type of nutrition is used: heterotroph; heterotroph that is a saprotroph; heterotroph that is a detritivore; autotroph.

(a) The bacterium *Rhizobium*.
(b) Fungi on a dead log.
(c) Cyanobacteria floating where there is sunlight.
(d) A snail scraping algae off a rock.



Rhizobium lives in the root nodules of legumes and fixes atmospheric nitrogen. These bacteria are symbiotic and receive carbohydrates and a favourable environment from their host plant.

Fungi on a dead log.

The sustainability of ecosystems

Thanks to this recycling of nutrients, ecosystems can continue to be productive and successful for long periods of time. The producers take simple inorganic compounds, such as carbon dioxide (CO_2), from their environment and convert them into energy-rich sugars, such as glucose ($C_6H_{12}O_6$). Those simple sugars can then be transformed into complex carbohydrates to make cellulose, to build up plant cell walls. Other nutrients can be added to form complex organic molecules such as lipids and proteins.

Consumers will then come along and eat the producers, and digest the complex organic compounds into simpler building blocks, such as amino acids and sugars, for growth and energy. When those consumers die, their cells and tissues are broken down by decomposers, and the minerals are returned to the soil. Producers can once again absorb the nutrients from the soil, and grow new sources of food. The cycle is complete. This process is sometimes informally referred to as the circle of life, but the more scientific term is nutrient cycling.

One example of nutrient cycling is the nitrogen cycle. Nitrogen is extremely important to living organisms, as it is one of the elements needed in nucleotides and amino acids, the building blocks of life. Without this element, organisms would not be able to make DNA or proteins, and thus life would be impossible. Nitrogen starts the cycle in gas form in the atmosphere, as N_2. Plants and animals are incapable of using nitrogen gas but some bacteria are able to transform it into useful forms, such as nitrates, in a process called nitrogen fixation. These usable nitrates are absorbed by plant roots (which is why some plants host the nitrogen-fixing bacteria in their root nodules, as seen in the Challenge yourself photo above), and so the plants pass on nitrogen-rich nutrients when they are consumed by animals. Both plants and animals return the nitrogen to the soil in a variety of ways. Urine and faeces, for example, contain

nitrogen compounds, which is why farmers often put animal manure on the fields where they grow crops. When plants and animals die, the nitrogen compounds are returned to the ground by decomposition. Going back to the question at the start of the chapter, about what you would bring to the Moon to live there, would you have listed decomposers? What about nitrogen-fixing bacteria?

A miniature world in a plastic bottle

You can set up your own ecosystem of microbes in a plastic bottle at home or in the lab. This is a long-term project, so make sure you have somewhere that you can leave the bottle for many weeks or months. The experiment you're going to set up is called a Winogradsky column.

For this lab, you will need some dark, wet mud. If you get it near a pond, be sure to take some pond water separately as well. Make sure you have permission to take the samples.

You will need an empty, clean transparent plastic drinks bottle that will hold 2 or 3 litres, mud (nice, slimy, stinky, mud works the best), shredded newspaper, crushed egg shells and raw egg yolk.

- Place the last three ingredients in about half a litre of mud, removing any large pieces from the mud such as sticks and stones. Mix the ingredients up and pour them into the bottom of the bottle. A funnel might be necessary. Add more mud on top of that until the bottle is two-thirds full. Add some water, but be sure to leave about 5 cm of air at the top of the bottle. Be sure there are no air bubbles in the mud.
- Place the cap on the bottle and leave it for many weeks near a sunny window: the micro-organisms in the bottle need sunlight. It is a good idea to take a photo at the beginning of the experiment, and then one every week or so. These photos will show you the changes that occur over time. Make sure you carefully label your experiment so that no one throws it away thinking it is rubbish.

Variations on the experiment include using: a glass container that can be sealed at the top; different types of mud; different sources of carbon dioxide instead of the egg shells; different sources of sulfur instead of the raw egg yolk.

To interpret the results you will have to do a bit of research to find out what the different colours mean. Each one represents a different kind of bacterial colony in the mud, and each of those transforms molecules for the others to use. As long as there is light entering the system, the column will continue to maintain a healthy microbial ecosystem for many months.

If you have the materials, the time, and the ambition, it is also possible to set up a more complex aquatic ecosystem that is hermetically sealed. Go to the hotlinks for suggestions of web sites that explain how to do this. Otherwise, do a search for keywords such as 'make your own ecosphere' or 'sealed terrarium'.

Ethical considerations: in accordance with the IB policy on the use of living organisms in experiments, it is best to avoid putting sentient beings in your ecosphere or mesocosm. Before adding snails or shrimp, for example, you would need to decide if you can justify exposing such organisms to things they would not encounter in their natural habitat such as low oxygen levels or low food supplies. Fish, tadpoles, or invertebrates bigger than a few millimetres are probably not appropriate.

Two major events in the modern environmental movement were the first photographs of Planet Earth from space, during the Apollo missions in the late 1960s and early 1970s, and the publication in 1962 of *Silent Spring* by Rachel Carson, a book imagining a future with no more birds.

In the decades since those events, more and more people have become concerned about our ability as a species to have enough space, water, and food for everyone. Ecologists who study human interactions with the other forms of life on Earth, and interactions with the non-living components of the environment, are concerned about our future, and think that international cooperation is necessary to solve complex global issues such as insufficient drinking water supplies, overfishing, global climate change, loss of forests and topsoil, bleaching of coral reefs, and the depletion of countless other natural resources. Their plea is that we need to adopt international policies to limit human impact and maintain sustainable practices.

Governments and societies are going to need to think about what is necessary for this to happen. Several paths could be explored, such as better education, international agreements and policies, higher taxation of unsustainable activities, or discussions of population control to limit human impacts. All of these have advantages and disadvantages and would need to be debated. One phrase that often comes up when looking for ways in which we can help our planet is 'act locally, think globally'. This could be a possible topic for discussion in your biology class or TOK class.

To learn more about micro-ecosystems setting up sealed mesocosms, go to the hotlinks site, search for the title or ISBN, and click on Chapter 4: Section 4.1.

Exercises

1. Distinguish between habitat and ecosystem.
2. Explain why decomposers are so important in nature.
3. Humans can be considered to be omnivores, meaning they eat autotrophs and heterotrophs. Give two examples of autotrophs in the human diet and two examples of heterotrophs in the human diet.

NATURE OF SCIENCE

Use theories to explain natural phenomena: the concept of energy flow explains the limited length of food chains.

4.2 Energy flow

Understandings:

- Most ecosystems rely on a supply of energy from sunlight.
- Light energy is converted to chemical energy in carbon compounds by photosynthesis.
- Chemical energy in carbon compounds flows through food chains by means of feeding.
- Energy released from carbon compounds by respiration is used in living organisms and converted to heat.
- Living organisms cannot convert heat to other forms of energy.
- Heat is lost from ecosystems.
- Energy losses between trophic levels restrict the length of food chains and the biomass of higher trophic levels.

Applications and skills:

- Skill: Quantitative representations of energy flow using pyramids of energy.

Guidance

- *Pyramids of number and biomass are not required. Students should be clear that biomass in terrestrial ecosystems diminishes with energy along food chains, due to loss of carbon dioxide, water, and other waste products, such as urea.*
- *Pyramids of energy should be drawn to scale and should be stepped, not triangular. The terms producer, first consumer, and second consumer, and so on should be used, rather than first trophic level, second trophic level, and so on.*
- *The distinction between energy flow in ecosystems and cycling of inorganic nutrients should be stressed. Students should understand that there is a continuous but variable supply of energy in the form of sunlight but that the supply of nutrients in an ecosystem is finite and limited.*

The importance of sunlight to ecosystems

Sunlight is the initial source of energy for all vegetation.

The best studied ecosystems are those found on Earth's surface, whether they are on land or in surface water. Such systems rely on sunlight, and they will be the main focus of this section. Be aware, however, that there are other, less well-studied, ecosystems that exist in total darkness, such as those in deep ocean water and those found deep underground, but these are not well understood because they are so difficult to access.

All life that you see around you on Earth's surface relies either directly or indirectly on sunlight. If a person eats an omelette for breakfast, for example, the eggs were made indirectly with energy from sunlight. How? The hen that laid the eggs probably ate some kind of grain in order to get the energy to make the eggs, and the plant material eaten by that hen was from a producer, and the producer used sunlight to transform carbon dioxide and water into energy-rich carbon compounds. Take away the sunlight from this scenario, and the eggs could not have been produced because the hen would not have had any grains to eat.

The role of photosynthesis

As seen in Section 4.1, photosynthetic organisms such as phytoplankton and plants take simple inorganic carbon dioxide, CO_2, and convert it into energy-rich sugar, $C_6H_{12}O_6$. The addition of minerals allows the producers to synthesize complex molecules such as cellulose, proteins, and lipids. Notice what is happening in this process: light energy from the Sun is being converted into chemical energy (food). Chemical energy refers to the fact that organic compounds, such as carbohydrates, proteins, and lipids, are rich in energy, thanks to the chemical bonds that exist between the carbon atoms and other atoms. This is what makes fruits, grains, and vegetables good food sources. Consumers cannot 'eat' sunlight and air, but they can eat carbohydrates, proteins, and lipids. The chemical energy in these organic compounds can be measured in calories or kilocalories, which we see listed on food packaging. One way to release the chemical energy from organic compounds is to digest the food, another way is to burn it. Burning wood in a fire is a good example of turning chemical energy in the organic compounds of the wood into light energy (and heat energy).

Food chains

By feeding on producers, consumers can utilize the chemical energy to grow and stay healthy. For example, a cow (the consumer) grazing in a field of grass (the producer) is taking chemical energy from the grass and digesting the organic compounds to help build meat or milk inside its own body. Humans can consume the meat or milk from the cow to benefit from the chemical energy the cow has obtained from the grass. Such a pattern of feeding is called a food chain. The process of passing energy from one organism to another through feeding is referred to as the flow of energy through a food chain.

When studying feeding habits, it is convenient to write down which organism eats which by using an arrow. Thus, herring → seal indicates that the seal eats the herring. When the seal's eating habits are investigated and the herring's diet is considered, new organisms can be added to the chain: copepods (a common form of zooplankton) are eaten by the herring, and great white sharks eat seals. Lining up organisms with arrows between them is how food chains are represented. Here are three examples of food chains from three different ecosystems.

Grassland ecosystem:

grass → grasshoppers → toads → snakes → hawk

River ecosystem:

algae → mayfly larvae → juvenile trout → kingfisher

Marine ecosystem:

diatoms → copepods → herring → seals → great white shark

The definition of a food chain is a sequence showing the feeding relationships and energy flow between species. In other words, it answers the question 'What eats what?' The direction of the arrow shows the direction of the energy flow.

Biologists use the term trophic level to indicate how many organisms the energy has flowed through.

The first trophic level is occupied by the autotrophs or producers. The next trophic level is occupied by the primary consumers (organisms that eat the producers), and the trophic level after that is occupied by secondary consumers (organisms that eat primary consumers).

Three trophic levels can be seen in this photograph: a producer, a primary consumer, and a secondary consumer.

Cellular respiration and heat

In the example of the grass and the grasshoppers, inside a grasshopper chemical energy is used for cellular respiration. Glucose originally produced by the grass is converted by the grasshopper's cells into carbon dioxide and water. This chemical reaction generates a small amount of heat in each of the grasshopper's cells. Any heat

generated by cellular respiration is lost to the environment. Although this might be more obvious in mammals, which can give off considerable amounts of heat, even grasshoppers will lose heat to the environment. If the grasshopper is eaten, some of the chemical energy in its body (in the form of protein, for example) is passed on to the next organism (a toad, for example). If the grasshopper dies and is not eaten, detritivores and decomposers will use its available energy.

The cells of decomposers also carry out cellular respiration and, as a result, any heat produced this way will also be lost to the environment. This is just one source of energy loss from one trophic level to the next, as we will see.

How many trophic levels are shown in this Peruvian scene?

Heat cannot be recycled

This section has mentioned heat being lost, but what does it mean when heat is 'lost'? As you may already know from other science courses, there is a law about energy stating that energy cannot be created or destroyed, only converted from one form to another. We have seen that light energy can be converted into chemical energy by the process of photosynthesis. We have also seen that during the process of cell respiration, not all the energy is converted into useful energy (ATP) by the cell: some of it is converted to heat energy. Although this keeps mammals warm, once the heat leaves an organism's body, it cannot be used again as a biological energy resource. So, for the organism, this energy is 'lost'. It has not disappeared, however; it has simply been converted into a form that the organism can no longer use as a source of energy.

The most popular theory for the mass extinction that wiped out the dinosaurs (and many other organisms) at the end of the Cretaceous period, is that the Sun's energy was blocked by particles in the air after a large object smashed into Earth. The darkened skies meant that producers could not get enough sunlight to continue making enough food to feed the consumers.

Where does the heat go?

Because ecosystems are made up of lots of respiring organisms, each losing heat, heat is lost from the ecosystem. Once the heat has radiated into the surrounding environment, the ecosystem cannot take back that heat to use it. Notice how this is very different from nutrient cycling with substances such as nitrogen and carbon. Unlike nutrients, energy cannot be recycled. It is passed from one trophic level to the next, and when it leaves the ecosystem it is not reusable. Is this a problem? Usually no, because the Sun is constantly providing new energy to producers. The energy is converted to chemical energy and passed on from one trophic level to the next. However, if, for some reason, the Sun stops shining, because it is blocked from Earth by clouds or particles in the sky (as happens after large volcanic eruptions), then the food chain is affected.

Only chemical energy can be used by the next trophic level (see Figure 4.2), and only a small amount of the energy that an organism absorbs is converted into chemical energy. In addition, no organism can use 100% of the energy present in the organic molecules of the food it eats. Typically, only 10–20% of the energy available is used from the previous step in a food chain. This means that as much as 90% is lost at each level.

Here are the main reasons why not all of the energy present in an organism can be used by another organism in the next trophic level.

- Not all of an organism is swallowed as a food source, some parts are rejected and will decay.
- Not all of the food swallowed can be absorbed and used in the body, for example owls cough up the hair and bones of the animals they eat, and undigested seeds can be found in the faeces of fruit-eating animals.
- Some organisms die without having been eaten by an organism from the next trophic level.
- There is considerable heat loss as a result of cellular respiration at all trophic levels (shown by the wavy arrows in Figure 4.2), although the loss of heat varies from one type of organism to the next. Most animals have to move, which requires much more energy than a stationary plant needs. Warm-blooded animals need to use a considerable amount of energy to maintain their body temperature.

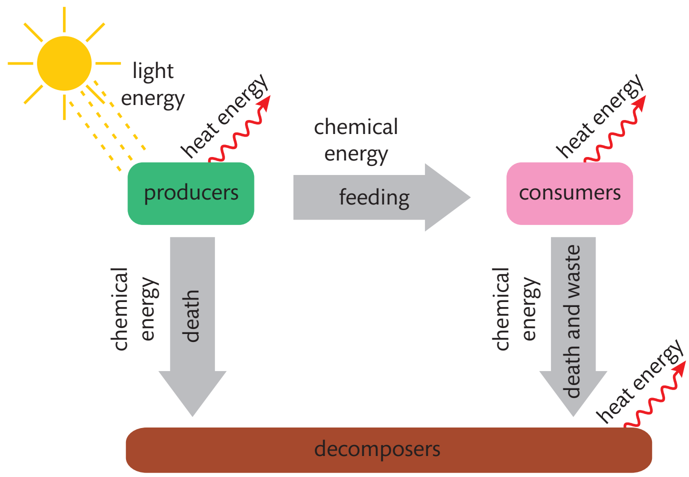


Figure 4.2 Energy flow and energy loss.

Whereas nutrients are constantly cycled in ecosystems, energy is not. The cycles of growth, death, and decomposition show how nature recycles nutrients, but energy pyramids show that energy flows through a system and is lost. This is why new energy must arrive in the form of sunlight in order to keep the system going.

Pyramid of energy

A pyramid of energy is used to show how much and how fast energy flows from one trophic level to the next in a community (see Figure 4.3). The units used are energy per unit area per unit time: kilojoules per square metre per year (kJ $m^{-2} yr^{-1}$). Because time is part of the unit, energy pyramids take into account the rate of energy production, not just the quantity.

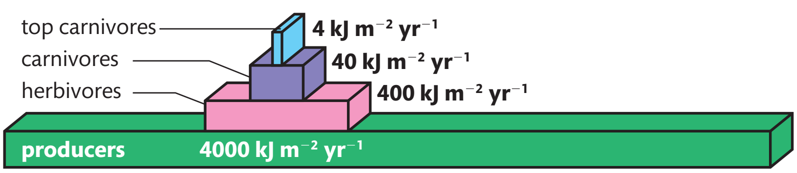


Figure 4.3 Pyramid of energy.

Because energy is lost, each level is always smaller than the one before. It would be impossible to have a higher trophic level wider than a lower trophic level, for example, because organisms cannot create energy, they can only transfer it inefficiently.

Be careful not to confuse pyramids of energy with pyramids of numbers: pyramids of numbers show the population sizes of each trophic level, not the energy.

Worked example

Using the following information, construct a pyramid of energy. Try your best to make it to scale.

In an ecosystem, the producers make 10 000 kJ m^{-2} yr^{-1}. 1000 kJ m^{-2} yr^{-1} of energy is passed on to the herbivores. In the third trophic level, the carnivores absorb 100 kJ m^{-2} yr^{-1} and the top predators who eat them get 10 kJ m^{-2} yr^{-1}.

Solutions

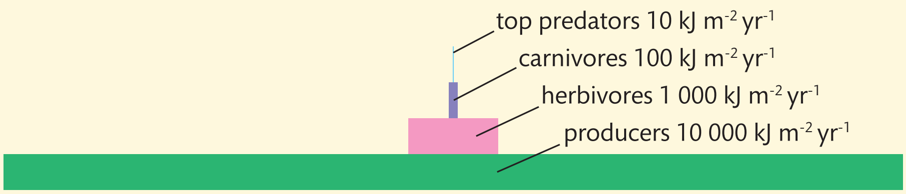


Figure 4.4 A pyramid of energy showing a 90% loss of energy at each trophic level.

Food webs and energy levels in trophic levels

If you look back at the three examples of food chains earlier in this chapter, you will notice that they are all either four or five organisms long. Although some food chains can have up to six trophic levels, most have four. The number of levels is limited by how much energy enters the ecosystem. Because so much is lost at each level, low energy at the start will quickly be lost, whereas abundant energy at the start can sustain several trophic levels. So the number of organisms in the chain as well as the quantity of light available at the beginning will determine how long the chain is.

The biomass of a trophic level is an estimate of the mass of all the organisms within that level. It is expressed in units of mass, but also takes into account area or volume. For example, in terrestrial ecosystems, fields of wheat might produce 1 tonne $acre^{-1}$ yr^{-1} in one area of the world, whereas another area might produce 3 tonnes $acre^{-1}$ yr^{-1}. Although there may be other factors, the amount of sunlight reaching the fields will influence the biomass, so that sunnier parts of the world can produce more wheat. In contrast, cooler climates or ones with fewer hours of sunlight per year have a lower biomass and therefore cannot support as many organisms. The fields of wheat could be the start of a food chain that consists of field mice, snakes, and hawks. Some molecules along the food chain cannot participate in the accumulating biomass because they are lost in various forms: carbon dioxide is lost from the organisms during cellular respiration, water is lost during transpiration and evaporation from the skin, and waste products including urea are excreted. So, just as not all energy gets passed on from one trophic level to the next, not all biomass gets passed on either.

Look at the food chains in Figure 4.5 showing a river ecosystem. Notice how the trophic levels link together into a food web. Sometimes it is necessary to describe a food web, rather than a food chain, because an organism such as a juvenile trout eats not only caddis fly larvae but also the larvae of other species. Notice that the trophic levels are labelled with the letter T, and think about the biomass in each: did you ever wonder how scientists estimate the total biomass in each trophic level? That question

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The statements about what limits the length of a food chain and prevents one from going beyond a certain number of trophic levels can be explained by the energy pyramids shown earlier. Because so much energy is lost at each level (90%), the only way to have more energy available for the top level is to increase the energy going into the bottom level, for the producers. As the energy collected by producers is limited by the amount of sunlight reaching Earth's surface, it is difficult to increase it.

goes beyond the scope of this section, but, if you are interested, use the hotlinks at the end of this section to find more information.

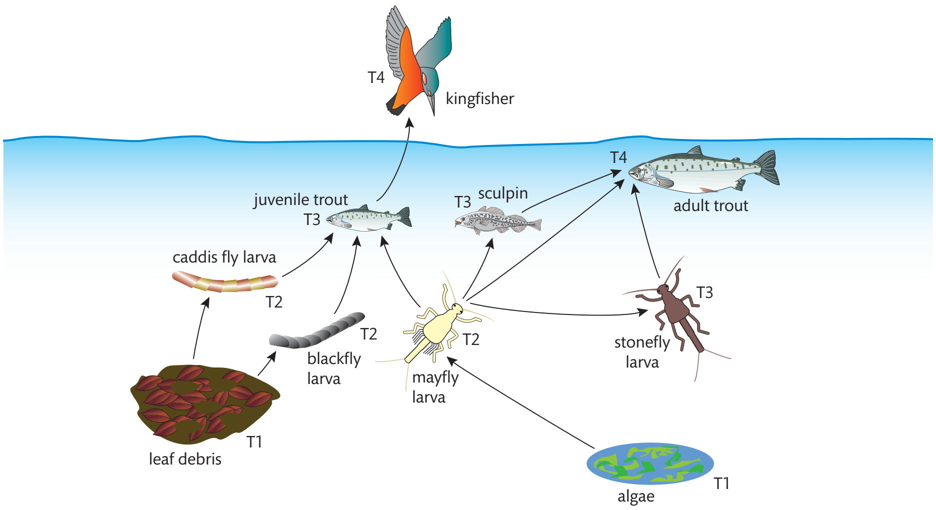

Figure 4.5 A food web from a river ecosystem showing trophic (T) levels.

To learn more about biomass, go to the hotlinks site, search for the title or ISBN, and click on Chapter 4: Section 4.2.

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Ever since Thomas Malthus predicted in the late 18th century that humans would eventually run out of food, scientists and researchers have wondered how big the human population can get before the amount of biomass available as food becomes insufficient to feed everyone. Techniques of food production have changed dramatically since Malthus' time, and we have not yet reached the tipping point he predicted. The industrialization of agriculture, as well as the invention of artificial fertilizers, brought about the Green Revolution, allowing farmers to produce many times more biomass than ever before on the same farms. Today, in some countries, tonnes of grain sit and rot in silos, while in other countries people go hungry. Are questions of world hunger simply questions of technology and biomass production? Do we need to produce more food to feed the hungry? Will the Malthusian catastrophe eventually come about: will we run out of food for our species some day? Or should we be confident that countries will work together to find the best solution? What questions do scientists still need to answer in order to guide policy makers, and how will they answer those questions?

Exercises

4 Look at these food chains again. Name the trophic levels (as producer or consumer) for each organism listed.

(a) Grassland ecosystem:
grass → grasshoppers → toads → snakes → hawk

(b) River ecosystem:
algae → mayfly larvae → juvenile trout → kingfisher

(c) Marine ecosystem:
diatoms → copepods → herring → seals → great white shark

5 From the following information, construct a food web:

- grass is eaten by rabbits, grasshoppers, and mice
- rabbits are eaten by hawks
- grasshoppers are eaten by toads, mice, and garter snakes
- mice are eaten by hawks
- toads are eaten by hognose snakes
- hognose snakes are eaten by hawks
- garter snakes are eaten by hawks.

6 From the food web you have drawn, what is the trophic level of the toad?

4.3 Carbon cycling

Understandings:

- Autotrophs convert carbon dioxide into carbohydrates and other carbon compounds.
- In aquatic ecosystems carbon is present as dissolved carbon dioxide and hydrogen carbonate ions.
- Carbon dioxide diffuses from the atmosphere or water into autotrophs.
- Carbon dioxide is produced by respiration and diffuses out of organisms into water or the atmosphere.
- Methane is produced from organic matter in anaerobic conditions by methanogenic archaeans and some diffuses into the atmosphere or accumulates in the ground.
- Methane is oxidized to carbon dioxide and water in the atmosphere.
- Peat forms when organic matter is not fully decomposed because of acidic and/or anaerobic conditions in waterlogged soils.
- Partially decomposed organic matter from past geological eras was converted either into coal or into oil and gas which accumulates in porous rocks.
- Carbon dioxide is produced by the combustion of biomass and fossilized organic matter.
- Animals such as reef-building corals and molluscs have hard parts that are composed of calcium carbonate and can become fossilized in limestone.

Applications and skills:

- Application: Estimation of carbon fluxes due to processes in the carbon cycle.
- Application: Analysis of data from air monitoring stations to explain annual fluctuations.
- Skill: Construct a diagram of the carbon cycle.

Guidance

- *Carbon fluxes should be measured in gigatonnes.*

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Making accurate, quantitative measurements: it is important to obtain reliable data on the concentration of carbon dioxide and methane in the atmosphere.

Carbon

As seen in Chapter 2, the element carbon is the cornerstone of life as we know it. Carbon is such a crucial element to living organisms that it is part of the definition of a living thing. You will recall that the term 'organic' implies that carbon is present. Hence, life on Earth is referred to as carbon-based life.

Not only is carbon found in the biosphere in organic molecules such as carbohydrates, proteins, lipids, and vitamins, it is also found in the atmosphere as carbon dioxide and in the lithosphere as carbonates and fossil fuels in rocks. The biosphere refers to all the places where life is found, and the lithosphere refers to all the places where rocks are found. Petroleum, from which products such as gasoline, kerosene, and plastics are made, is rich in carbon because it originated from partially decomposed organisms that died millions of years ago.

As seen in Figure 4.6, carbon is constantly being cycled between living organisms and inorganic processes that allow the carbon to be available. The carbon atoms that make up the cells of the flesh and blood of the giraffe, for example, came from the vegetation the giraffe ate. Eating organic material provides newly dividing cells in the giraffe's body with a fresh supply of carbon-based energy-rich molecules with which the cells can carry out work. When cellular respiration is complete, carbon dioxide is released into the atmosphere, and when the giraffe dies, its body will be eaten by scavengers and the remains broken down by decomposers. Some of the carbon from the giraffe's body will go back into the atmosphere as carbon dioxide when the decomposers perform cellular respiration. This section will look at some of the many different forms carbon can take as it is cycled by nature.

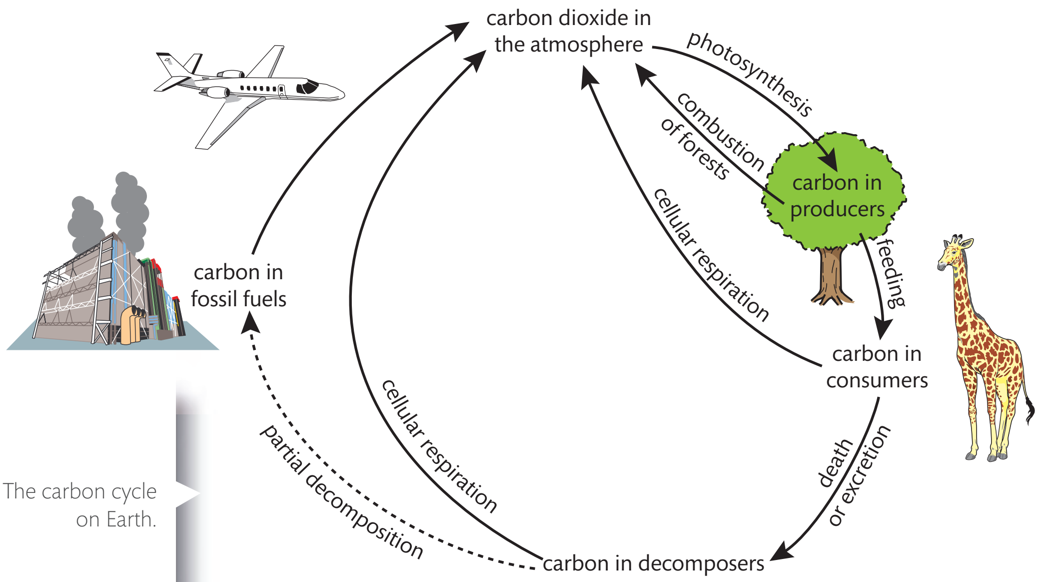


Figure 4.6 The carbon cycle on Earth.

The role of autotrophs in the carbon cycle

Let's start with food. Photosynthetic autotrophs take carbon dioxide from the atmosphere and convert it into carbohydrates. Here is the unbalanced chemical equation for photosynthesis.

	inorganic carbon dioxide goes in	→	an organic carbohydrate (glucose) comes out	
H_2O +	CO_2	→	$C_6H_{12}O_6$	+ O_2

Figure 4.7 The unbalanced equation for photosynthesis.

The sugar on the right-hand side of the equation (in green) is a source of food, not only to the autotroph synthesizing it, but also to the organisms that feed on the autotrophs. In its inorganic form on the left, as atmospheric carbon dioxide (in blue), the carbon is not usable as a food source by the autotrophs or by any consumers. Few people fully realize how dependent the biosphere is on energy from the Sun for food production. And the biosphere includes us.

Do you use cellulose in your life? You are probably wearing cellulose right now, because any textiles made of cotton are made of plant cellulose. Books are printed on cellulose, because paper pulp is from plant material. And if you use a car or a bus that runs on biofuel, that vehicle is being powered by cellulose.

From the $C_6H_{12}O_6$ molecules, autotrophs can manufacture other compounds. Fructose and galactose are other sugars that can be made by plants from glucose. Connecting the sugars together into a long chain can make starch; plants can store energy for a future season or a future generation in the form of starch granules, tubers, or seeds. Plants and algae need to build their cell walls with cellulose, which is also made from long chains of glucose. Glucose is the starting point for making other organic compounds that are not carbohydrates, such as lipids and amino acids. These compounds are necessary to make useful things such as cell membranes and proteins such as enzymes. To synthesize these non-carbohydrates, other elements such as nitrogen must be added to the glucose.

Carbon in aquatic ecosystems

As you know from drinking fizzy drinks or carbonated water, carbon dioxide can dissolve in water. Although the oceans, lakes, and rivers of the world are not as fizzy

as a carbonated drink, they contain dissolved carbon dioxide because carbon dioxide from the atmosphere can be absorbed by the water. Remember also that organisms living in water produce carbon dioxide through cellular respiration. As the carbon dioxide is dissolved in the water, it forms an acid. The pH of water decreases as the amount of carbon dioxide increases. This is why carbonated water has an acidic taste.

$$CO_2 + H_2O \rightarrow H_2CO_3 \text{ (carbonic acid)}$$

$$H_2CO_3 \rightarrow H^+ + HCO_3^- \text{ (hydrogen carbonate ion)}$$

When dissolved in water, the carbonic acid forms the H^+ in the equation above, which is an ion that can influence pH. But what is of interest to us is the hydrogen carbonate ion, HCO_3^-, because this is a good example of an inorganic carbon-based molecule that participates in the carbon cycle.

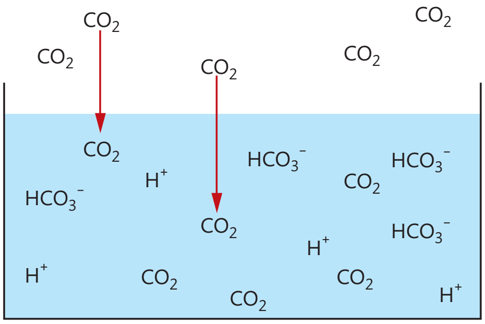


Figure 4.8 The forms of carbon available in aquatic ecosystems: dissolved carbon dioxide and hydrogen carbonate ions.

Cycling of carbon dioxide

Carbon dioxide is absorbed by photosynthetic autotrophs such as photosynthetic bacteria, phytoplankton, plants, and trees. As you will recall, these producers are eaten by consumers, which use the carbon in their bodies. Cellular respiration from all trophic levels, including decomposers, produces carbon dioxide, which is released back into the environment. This carbon dioxide diffuses into the atmosphere or into the water, depending on whether the organism is terrestrial or aquatic.

Carbon is available to photosynthetic organisms as carbon dioxide gas in the air or dissolved in water. It is available to consumers in the form of carbohydrates, proteins, and lipids, but can also be absorbed in the form of ions such as carbonate ions.

Methane in the carbon cycle

Other carbon compounds are produced by microbes such as archaeans. Members of the Archaea include methanogens, which are anaerobic (they live in environments with no oxygen). When these methanogenic archaea metabolize food, they produce methane (CH_4) as a waste gas. You should be familiar with methane because it is the same gas used in laboratories (the flame of Bunsen burners) and in homes for cooking and heating.

These microbes are also common in wetlands, where they produce marsh gas, which can sometimes glow mysteriously at night, but they are also responsible for producing methane gas in the digestive tracts of mammals, including humans. With large herds of cattle being raised worldwide, there is a concern that the quantities of methane they produce are contributing to the greenhouse effect, which will be discussed in the next section.

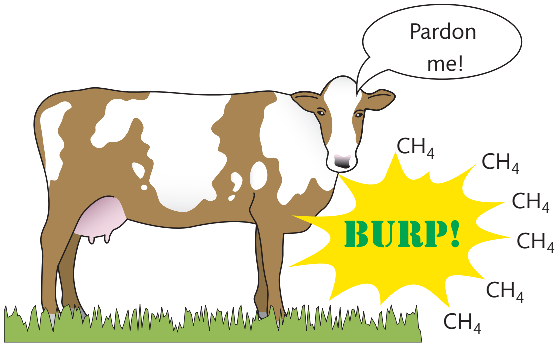


Figure 4.9 Methane gas production.

In her description of living in Biosphere II, a hermetically sealed experimental facility developed in Arizona, USA, researcher Jane Poynter said she had a new appreciation of the air she was breathing. In an interview on the TED Radio Hour in 2013 she said, 'The most profound experience I had in the biosphere was the experience of not only being completely dependent on my biosphere, but being absolutely a part of my biosphere in a very literal way. I mean, as I walked through the biosphere, I was incredibly conscious of the fact that the plants surrounding me were providing me with the oxygen that I needed to breathe, and that I was providing them some of the carbon dioxide they needed to grow.' She says we need to think about this when we are living in Biosphere I, which, in case you hadn't worked it out, is Planet Earth.

The oxidation of methane

How does the burning of fossil fuels produce carbon dioxide? Look at the chemical reaction below, showing methane burning in oxygen gas:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$$

Methane is the main ingredient in the fossil fuel we call natural gas. As you can see from the formula, this chemical reaction involves oxygen gas from Earth's atmosphere. When the methane is oxidized, the two molecules produced are water vapour and carbon dioxide gas.

The carbon found in the molecule CH_4 was borrowed from a CO_2 molecule that was removed from the atmosphere millions of years ago during photosynthesis. It then took the methane gas millions of years to form and accumulate underground. When we burn natural gas provided by the petroleum industry, we return that carbon to the atmosphere in the form of carbon dioxide. Normally, we would think that this is just part of a balanced cycle. The problem is, one part of the cycle takes millions of years and the other part, the burning of fossil fuels, is very rapid.

Peat as a fossil fuel

Another organic substance that can be used as a fossil fuel is partially decomposed plant material called peat. Peat is a kind of waterlogged soil found in certain types of wetlands, such as mires and bogs, which can be found in the British Isles, Scandinavia, northern Russia, some eastern European countries, northern Canada, northern China, the Amazon River basin, Argentina, northern USA (notably Alaska) and parts of Southeast Asia. Peat is very dark in colour and only certain types of vegetation can grow on its surface, such as sphagnum moss. Although peat is a heterogeneous mixture of many things, at least 30% of its dry mass must be composed of dead organic material for it to be called peat. The soil that forms peat is called a histosol, and a layer of peat is typically between 10 and 40 cm thick.

Slabs of peat left to dry in Scotland.

Walking on peatlands can be a bit of a challenge because they are very spongy. The high levels of water on peatland force out the air that would normally be between the soil particles. As a result, anaerobic conditions are created, which allows certain types of microorganisms to grow but prevents the growth of microorganisms that would

normally help in the decomposition of plant material. Hence many of the energy-rich molecules that would have been fed upon by decomposers are left behind and transformed, over thousands of years, into in energy-rich peat.

Another characteristic of peatlands is the pH of the waterlogged histosol: it is very acidic. Just as with low oxygen levels, if the acidity is not conducive to the decomposers, they will not be able to do their work. High acidity contributes to the fact that non-decomposed material accumulates. In the pools of acidic water that can be found on these wetlands, certain types of organisms can be found that are not found anywhere else, such as some species of aquatic beetles.

In order for it to be usable as a fuel, cut peat is dried out to reduce its high levels of humidity. It is cut into slabs, granules, or blocks, and moved to where it is needed. Like all fossil fuels, however, peat takes a very long time to form and is not considered to be a renewable source of energy. Once all the peat in a wetland has been harvested it is gone; it is unrealistic to wait for new peat to form, so new sources of fuel are needed.

In economic periods when oil prices are high, peat can be a competitive energy source, but when oil prices are low this is not the case, and there have been decades during which many countries decided to drain their wetlands to replace them with forests and farmland. In some cases, environmental concerns about the preservation of wetlands, because they are an important part of the ecosystem and a habitat for unique species, have prevented the digging and drainage of peatlands. Another reason to preserve wetlands is that pollen trapped in deep layers of the bogs thousands of years ago can provide evidence of what the climate was like in the past, giving us 'libraries' of biotic information.

Oil and gas as fossil fuels

In some cases, when left in the correct conditions, partially decomposed peat can be further transformed into coal. Over millions of years, sediments can accumulate above the peat, and the weight and pressure of those sediments compresses the peat. Under conditions ideal for the formation of coal, the sedimentation continues until the carbon-rich deposits are not only under huge pressure but also exposed to high temperatures because they have been pushed far below Earth's surface. The pressure and heat cause chemical transformations associated with lithification, which is the transformation of sediments into solid rock. During lithification, the molecules are compacted and rearranged. What is of great interest to industries using coal is the hydrocarbons, the long chains of carbon atoms attached to hydrogen atoms (see Figure 4.10).

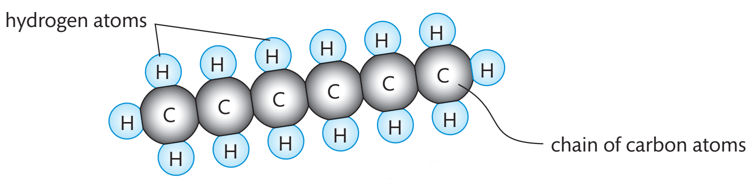


Figure 4.10 A hydrocarbon chain.

The C–H bonds hold a significant amount of energy, and, because there are many of them in long chains, each hydrocarbon molecule is rich in energy ready to be released by burning.

In order to use coal for energy, it must be extracted from below the ground, which is why mining is necessary. Coal is found in seams, where the layers of sediments were deposited, covered, and then transformed and often twisted and deformed by geological forces over millions of years.

A lump of coal.

In addition to coal, chemical transformations underground can produce other petroleum products, such as crude oil and, as we have seen, natural gas.

For this, we have to go far back in time, before dinosaurs roamed Earth. During the Carboniferous period, hundreds of millions of years ago, some places in the world that are now dry land were underwater and hosted abundant aquatic or marine life, including algae and zooplankton. For example, the dry deserts of Saudi Arabia used to be under the Tethys Ocean, back when all the continents were still stuck together in the supercontinent called Pangaea.

At that distant time in Earth's past, under conditions ideal for the formation of petroleum products, the dead remains of the organisms in the water did not fully decompose at the bottom of the ocean, and instead formed layers of sediment along with silt. In conditions lacking oxygen (anoxic conditions), the decaying material started to form sludge, as some parts of the organisms' cells decayed while others did not. One component of dead algae and zooplankton that is not easily broken down is the lipid component of their cells. Accumulated lipids that are trapped in sediments at the bottom of an ocean form a waxy substance called kerogen. It, too, is rich in hydrocarbons and, like the formation of other fossil fuels, is transformed by pressure and heat as sediments accumulate above it and cause its molecules to rearrange.

The natural production of kerogen is a long process, and the right conditions have only occurred in certain parts of the world. Figure 4.11 shows some of the places where crude oil has been found in the world.

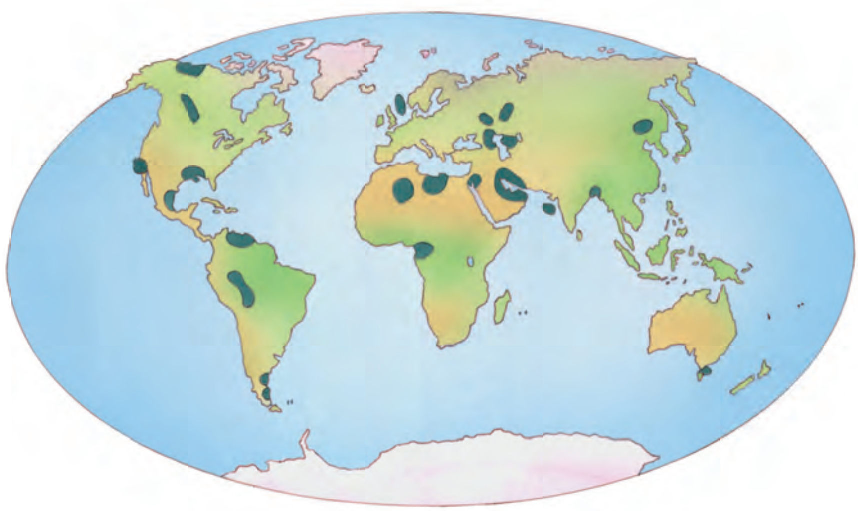
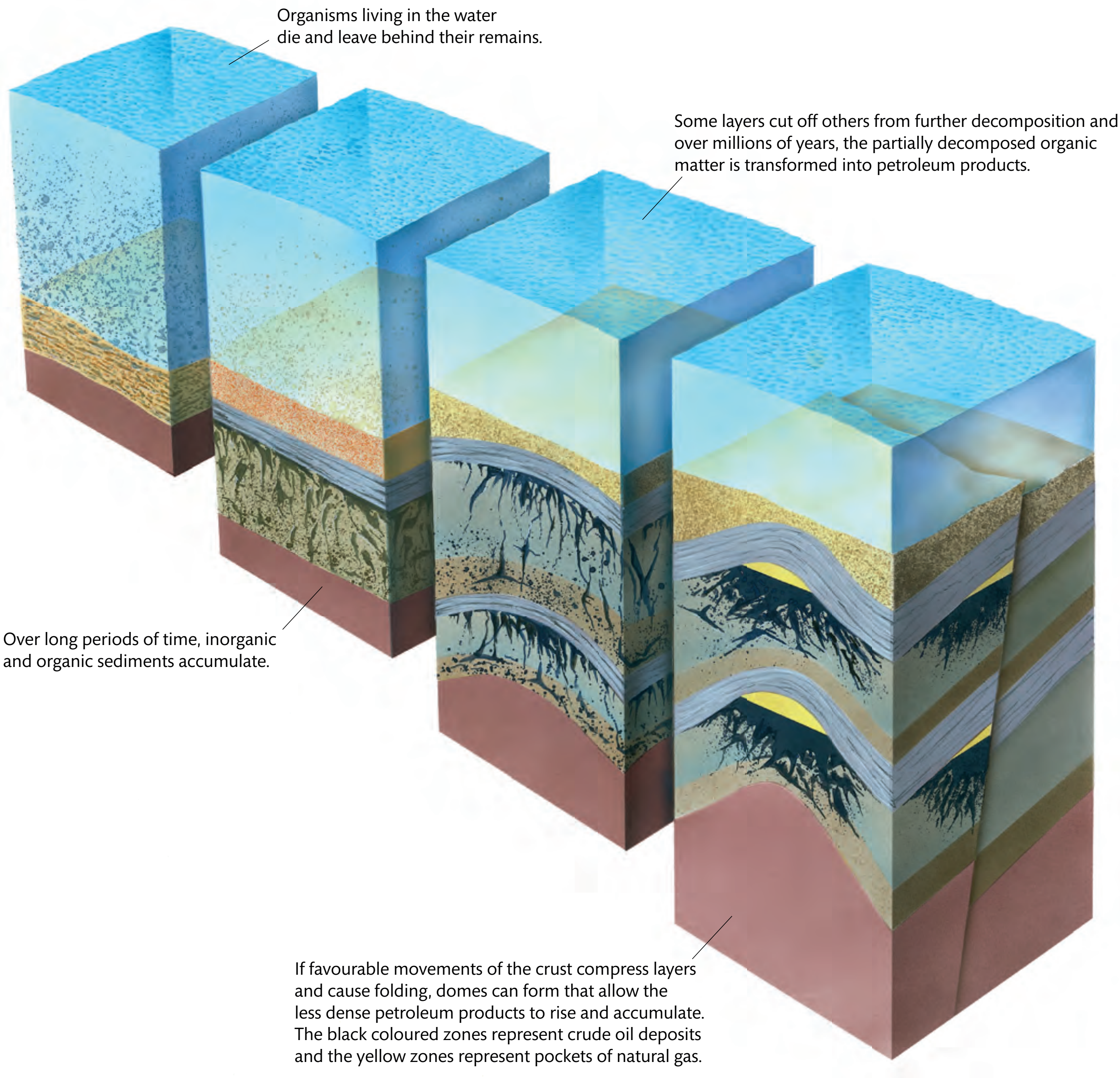


Figure 4.11 World deposits of crude oil.

Over millions of years, and after geological transformation, the kerogen in porous sedimentary rock becomes crude oil or, if it is in a gas state, natural gas. Both of these petroleum products are less dense than rock, so they tend to rise through cracks in the rocks towards the surface.

Figure 4.12 Formation of gas and oil.



In order to be used by humans, petroleum products must be trapped and pooled under a non-porous rock, preferably one that is bent by tectonic movement into a dome, as seen in Figure 4.12. This kind of formation allows large quantities of useful gas and oil to collect together in a productive reservoir. Geologists study the porosity and deformations of rock layers in order to determine which parts of the world might contain exploitable gas and oil reserves.

The term 'fossil fuel' refers to the fact that the source of energy in the fuel comes from partially decayed once-living organisms that died long ago, often millions or hundreds of millions of years ago. Because they take so long to form, fossil fuels are considered to be a non-renewable resource.

When an oil field is discovered and crude oil is pumped out of the ground, it is sent to refineries to be separated into the various products that we use every day, using an apparatus called a fractionating tower. Such an apparatus allows the heaviest, most dense molecules with the longest hydrocarbon chains to accumulate at the bottom, and the lightest, least dense molecules with the shortest hydrocarbon chains to accumulate at the top. Look at Figure 4.13 and see how many of these petroleum products you rely on every day. One fraction that is not shown in the diagram is naphtha, which might not sound familiar but it is the main ingredient used to make plastics.

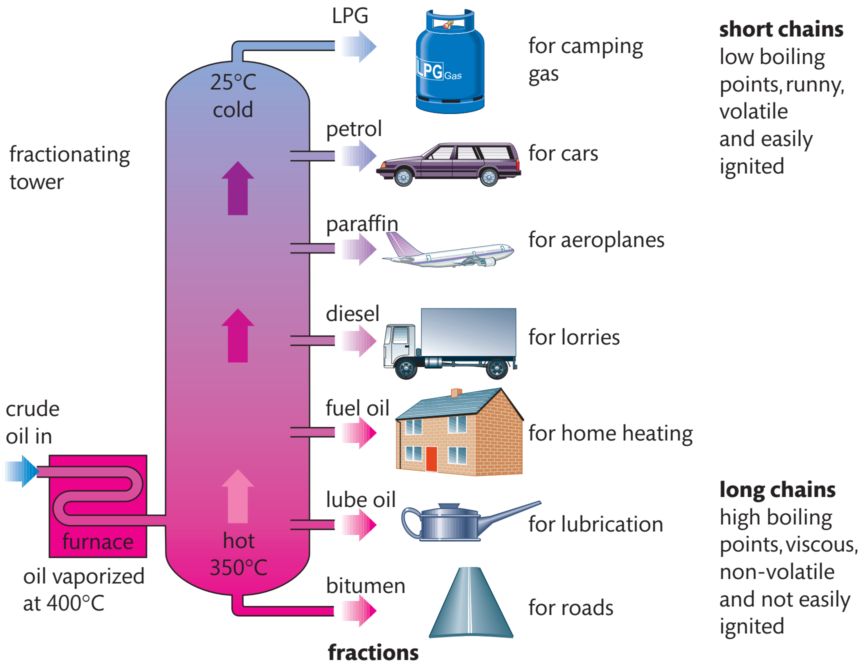


Figure 4.13 The many uses of petroleum products in our everyday lives. How many of these products do you rely on every day? One fraction that is not shown in the diagram is naphtha, which is the main ingredient used to make plastics.

Carbon dioxide is produced when fossil fuels are used

Just as we saw with methane previously, substances rich in hydrocarbons can be oxidized using oxygen gas from the atmosphere when they are burned. If you have ever made a fire on a beach or at a campsite, you know that organic material such as wood is capable of releasing a considerable amount of energy in the form of light and heat. Wood is not the only fuel of biological origin that can be burned: many people living in non-industrialized areas of the world use biomass in the form of animal dung as a source of energy. The dried dung of domesticated animals such as cows can be burned and used for various purposes, including cooking. Fresh, wet dung can be mixed with other refuse from a farm and put into a large container, where methane-producing microorganisms will decompose and ferment the material to produce flammable methane gas, as seen in Figure 4.14. Unlike fossil fuels, biofuels made in a biogas generator like this do not take millions of years to form.

Crude oil has the nickname 'black gold'. Oil and gas companies are prepared to go to the most inaccessible places in the world to dig out the black gold, whether it is in the hot sands of deserts or at the bottom of icy cold oceans. And it is worth all that trouble. In 2012, more than a third of the 50 companies with the highest revenues worldwide were oil and gas companies, four of which had revenues exceeding $400 000 000. Such a number is difficult to grasp, but it is higher than the gross domestic product (GDP) of most countries in the world.

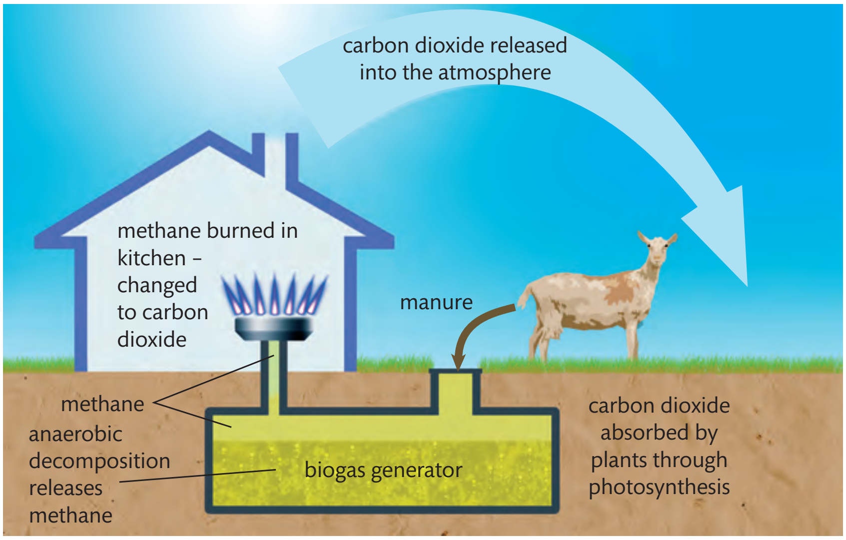


Figure 4.14 Biogas production and use.

In an effort to reduce fossil fuel consumption, some countries, such as the USA and Brazil, have introduced biofuel programmes using ethanol made from crops such as corn and soybeans. The plant material is fed to microorganisms that ferment it and in the process release ethanol. The ethanol is added to gasoline for vehicles, and contributes to a reduction in gasoline use. Standard vehicles cannot use more than 25% ethanol and need 75% or more gasoline (this mix can also be called gasohol), but vehicles specially adapted for biofuels can run solely on ethanol.

Using a different technique, biodiesel can be made from vegetable oils or animal fat. Some people have even modified their cars so that they run on the waste oil from deep-fat fryers at fast food restaurants.

Although it can be argued that using biofuels allows countries to reduce their dependence on imported fossil fuels, the burning of any biomass still releases carbon dioxide into the atmosphere. The difference is that, unlike fossil fuels, the carbon dioxide from biofuels was removed from the atmosphere by plants just a few months or years before the biofuel was used.

Some farmers in the world are growing crops that are not destined for human food nor for animal feed but rather for fuel to power cars and city buses. Brazil and the USA have been innovators in this practice, and it is a way of cycling carbon that depletes fewer fossil fuel reserves. There is a down side to it, however: some questions arise about the morality of such a practice. In the countries where this policy has been put in place, there are people starving. Is it acceptable to use food crops as fuel for motor vehicles instead of making it available for humans to eat? Critics point out that allocating farmland for this use might drive up the price of food crops.

Limestone

Marine organisms take dissolved carbon out of the water and use some of it to make their carbonate shells. As we saw earlier in this chapter, the carbon can be in the form of carbon dioxide dissolved in the water or it can be in the form of hydrogen carbonate ions. The organisms that build coral reefs are called coral polyps, and they absorb two ions from the seawater to build the reef: hydrogen carbonate ions and calcium ions. When combined, molecules of calcium carbonate ($CaCO_3$) are formed. This molecule is the basis of the coral reef, and it is sturdy like rock. Below is the chemical equation for making calcium carbonate:

$$Ca^{2+} + 2\,HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

Other organisms as well as coral polyps use calcium carbonate to build shells around their bodies. Molluscs (from the phylum Mollusca), such as snails, clams, oysters, and mussels, build up their shells with calcium carbonate and, when they die, the shells accumulate at the bottom of the ocean.

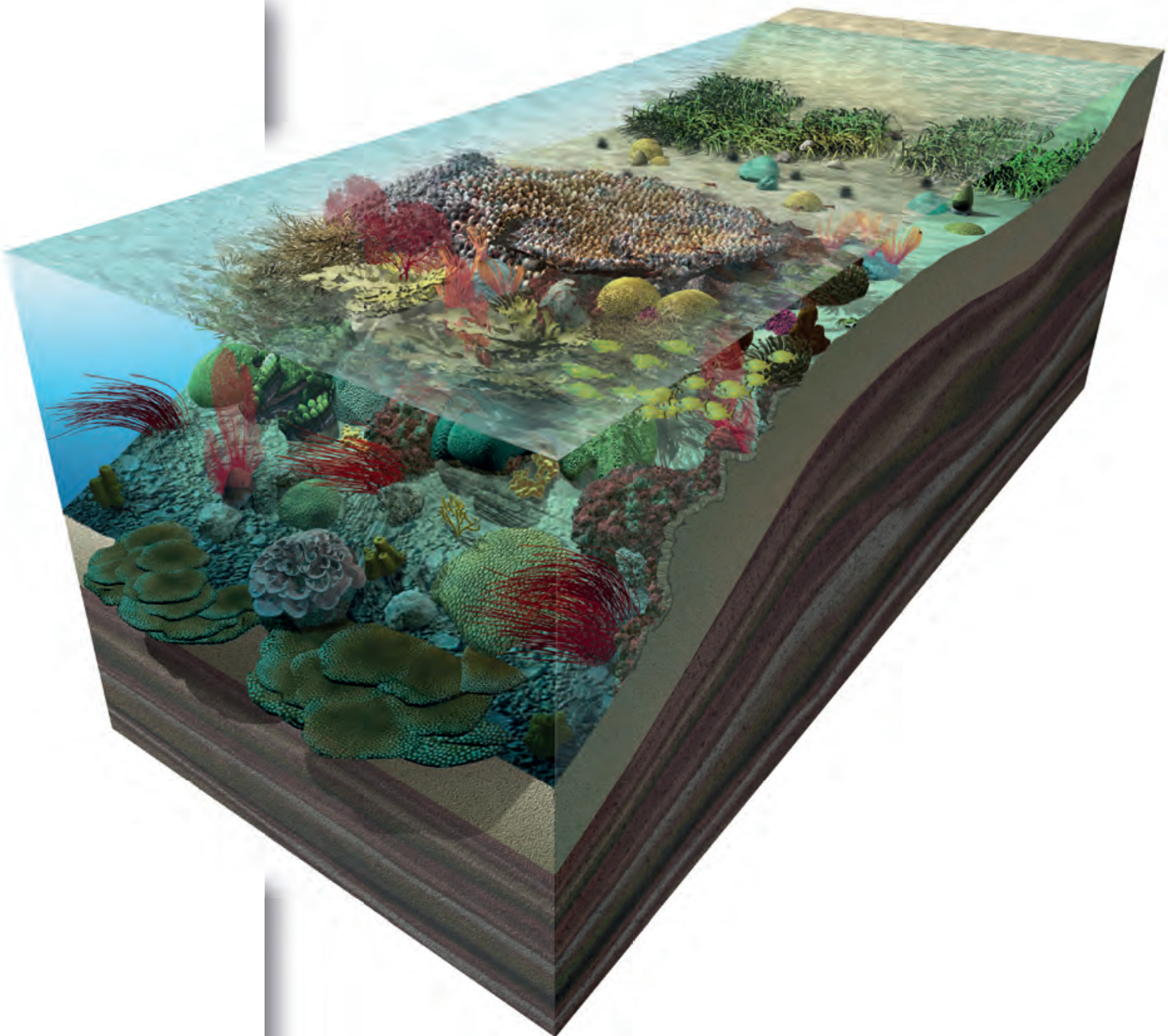


Figure 4.15 Coral reefs are formed from dissolved calcium and carbonate ions found in ocean water.

Microscopic foraminifera usually live on the ocean floor and are also very good at building shells, albeit very small ones. Because they are so numerous, however, and they have been around for hundreds of millions of years, their shells have accumulated in sediments, and when the sediments go through the process of lithification, they form limestone. Limestone has long been used by humans as a building material (the Great Pyramid at Giza and Notre Dame cathedral in Paris are two examples), and is a major ingredient in modern cement.

The process of taking carbon out of the environment and 'locking it up' in a substance for an extended period of time is called carbon sequestration, and when it happens naturally it is called biosequestration. This is one way balance is maintained in the carbon cycle.

Through biosequestration, an accumulation of foraminifera shells as sediments at the bottom of the ocean can trap carbon in limestone for millions of years. When cement is made by humans for construction, limestone is used and, in the process, some of the carbon is released back into the atmosphere as carbon dioxide, cancelling out the biosequestration.

CHALLENGE YOURSELF

4 Using Table 4.4, draw a flowchart showing the exchange of carbon between the atmosphere, the oceans, and the biosphere. Such exchanges are called fluxes and carbon fluxes in this table are expressed in gigatonnes of carbon per year (GtC yr^{-1}). You can do the drawing by hand but there are many flowchart tools available, both online and probably as part of the software on the computer you use.

Carbon fluxes	Quantity of carbon (GtC yr^{-1})
Examples of fluxes into the atmosphere	
Respiration of terrestrial organisms	120
Respiration of marine organisms at the surface of the ocean	92
Burning of fossil fuels (such as transport)	7.7
Changes in land use (such as deforestation)	1.5
Examples of fluxes out of the atmosphere	
Absorption of carbon dioxide into the water at the surface of the ocean	90
Gross primary production (GPP), photosynthesis of terrestrial organisms	90
Photosynthesis of marine organisms	40
Changes in land use (such as growing crops in prairies)	0.5
Weathering, carbon dioxide being incorporated into rocks and soils	0.2

Table 4.4 Carbon exchange into and out of the atmosphere

Exercises

7 Study Figure 4.16.

(a) Using the dark blue trend line, determine the atmospheric carbon dioxide concentration for 1965 and 2001.

(b) Calculate the percentage change from 1965 to 2001.

(c) Why do the measurements have a high point and a low point for each year?

(d) The photo insert shows the station where the measurements were taken, at the top of a volcanic island in the Pacific that is part of a USA state. Which state is the station in, and why did scientists decide to put the station there?

8 From what inorganic molecules can aquatic organisms get their carbon?

9 Give the names of the hydrocarbon-rich substances that are described below.

(a) A kind of waterlogged soil found in wetlands and made of partially decomposed plant material.

(b) A hard black rock that can be burned to make electricity or direct heat.

(c) A waxy substance formed from accumulated lipids trapped in sediments at the bottom of oceans.

(d) Of all the commonly used petroleum products, this one has the smallest density.

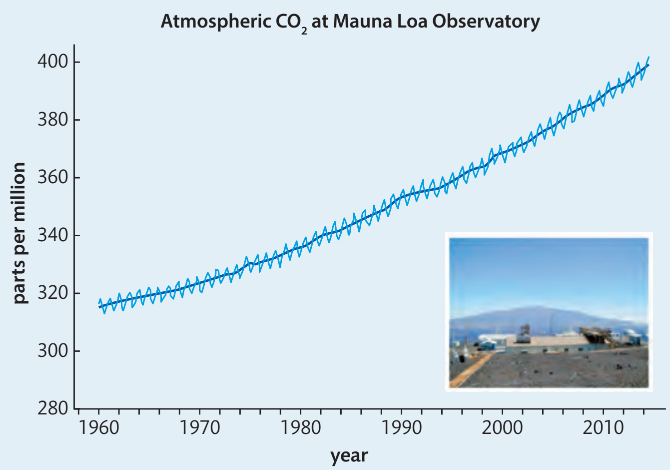
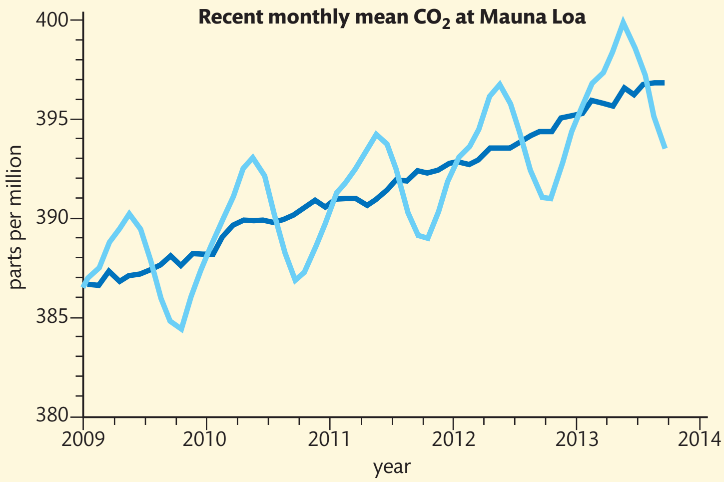


Figure 4.16 The National Aeronautics and Space Administration (NASA) data on carbon dioxide levels in the atmosphere 1958–2014. The up and down pattern is caused by seasonal fluctuations in activities such as photosynthesis. Dr Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/)

Worked example

You be the scientist: have a look at this graph from the website of the National Oceanic and Atmospheric Administration (NOAA), showing atmospheric carbon dioxide levels in recent years. This one is from October 2013, but you might be able to find a more recent one if you do a web search for the title.

Figure 4.17 Levels of atmospheric CO_2 from 2009 to 2014. Dr Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/)



The up-and-down pattern shown in light blue is caused by seasonal fluctuations in carbon dioxide levels. The dark blue line shows the trend corrected for these seasonal fluctuations.

1 **(a)** Work out how the years are divided up on the *x*-axis of the graph.

(b) Estimate the level of atmospheric carbon dioxide in January of 2010 and in October of 2013 using the corrected values on the dark blue trend line.

(c) Look at the first four lowest values on the light blue line. There is one per year. Determine the month of the year during which this low point most often occurs. Do the same for the high points.

2 **(a)** In terms of cellular respiration and photosynthesis rates in the northern hemisphere, explain the yearly downward fluctuations from May to October.

(b) Do the same for the upward fluctuations from October to May of the following year.

3 Describe the overall trend shown by the graph for the years shown, giving quantitative data in your description.

Solutions

1 **(a)** The years are divided into quarters: Jan/Feb/Mar, Apr/May/Jun, Jul/Aug/Sep and Oct/Nov/Dec.

(b) 388 p.p.m. and 397 p.p.m., respectively. It is important to include the units.

(c) Lows are in October and highs in May.

2 **(a)** As plants, phytoplankton, and photosynthetic bacteria are generally more active in the spring and summer months, more carbon dioxide is extracted from the atmosphere and levels drop. During this time, cellular respiration is contributing large quantities of carbon dioxide to the atmosphere, but not as fast as photosynthesis is taking it out.

(b) Conversely, when photosynthesis is less intense during the autumn and winter months, carbon dioxide levels rise and, although organisms are generally less active at colder times of the year, their cellular respiration rates put more carbon dioxide into the air than the photosynthetic organisms can remove.

3 The trend shows an increase from 387 p.p.m. at the beginning of 2009 to a 397 p.p.m. in October 2013. This 10 p.p.m. increase represents a percentage change of +2.6% for the period shown.

4.4 Climate change

Understandings:

- Carbon dioxide and water vapour are the most significant greenhouse gases.
- Other gases including methane and nitrogen oxides have less impact.
- The impact of a gas depends on its ability to absorb long-wave radiation as well as on its concentration in the atmosphere.
- The warmed Earth emits longer wavelength radiation (heat).
- Longer wave radiation is absorbed by greenhouse gases, which retain the heat in the atmosphere.
- Global temperatures and climate patterns are influenced by concentrations of greenhouse gases.
- There is a correlation between rising atmospheric concentrations of carbon dioxide since the start of the industrial revolution 200 years ago and average global temperatures.
- Recent increases in atmospheric carbon dioxide are largely due to increases in the combustion of fossilized organic matter.

Applications and skills:

- Application: Threats to coral reefs from increasing concentrations of dissolved carbon dioxide.
- Application: Correlations between global temperatures and carbon dioxide concentrations on Earth.
- Application: Evaluating claims that human activities are not causing climate change.

Guidance

- *Carbon dioxide, methane, and water vapour should be included in discussions.*
- *The harmful consequences of ozone depletion do no need to be discussed and it should be made clear that ozone depletion is not the cause of the enhanced greenhouse effect.*

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Assessing claims: assessments of the claims that human activities are not producing climate change.

The atmosphere

We live at the bottom of an ocean of air we call the atmosphere. It is so natural to us that we don't even think about it unless, for some reason, we are without it. When we go up in an airplane, for example, the cabin needs to be pressurized so that we can keep breathing, and so that we do not freeze to death 10 000 m above the ground. The atmosphere plays a vital role in regulating the temperature of Earth's surface.

Earth's surface has an average temperature of about 14°C; fluctuations only very rarely go lower than –80°C (in Antarctica) or higher than +50°C (in North Africa). In contrast, the Moon, which is the same distance from the Sun as Earth is, has temperature swings that typically go from –150°C to +120°C, depending on where sunlight is hitting the surface. This is because the Moon has almost no atmosphere. It is estimated that if Earth had no atmosphere, the average temperature would be 32°C colder (–18°C), making the possibility of life very different. We will see in this section how Earth's atmosphere acts as a kind of blanket, keeping us warm at night and sheltering us from excessive heat during the day.

The roles of carbon dioxide and water vapour in the greenhouse effect

The consequence of the Moon having little or no atmosphere is that it has no greenhouse effect. The greenhouse effect refers to a planet's ability to use its atmosphere to retain heat and keep warm even when no sunlight is hitting the surface. To understand the greenhouse effect, you need to know how a greenhouse works. The walls and roof of a greenhouse are made of glass. Sunlight penetrates through the

Seen from space along the edge of Earth's curve, the atmosphere is a surprisingly thin, almost insignificant looking, layer of gases.

glass and warms up the plants inside. Sunlight itself, which is made up of short wavelengths, is not warm; the temperature of outer space between the Sun and Earth is hundreds of degrees below freezing.

It is only when sunlight hits an object that some of its energy is transformed into heat. Heat energy, otherwise known as infrared radiation, has longer wavelengths than energy in the form of light. When sunlight goes through the glass of the greenhouse, it warms up the objects inside: the plants, the ground, and anything else inside. The objects inside radiate their heat to the air inside the greenhouse, but the glass of the greenhouse is not as transparent to heat energy as it is to light energy, so some of the heat is then trapped inside the greenhouse. The glass also plays a major role in preventing warm air from rising through convection to dissipate the heat. The result is that the temperature inside the greenhouse is warmer than outside. This helps plants to grow better when it is cold outside, which is one of the main reasons why farmers and gardeners use greenhouses.

Even if you have never been inside a greenhouse, you have probably felt the greenhouse effect when getting into a car that has been sitting in the sunshine with its windows closed on a hot day. The greenhouse effect on a planet is not caused by glass windows, but by its atmosphere's ability to retain heat in a similar way to that of the glass of a greenhouse or car.

The inside of a greenhouse

Greenhouse gases (GHGs), such as water vapour and carbon dioxide in Earth's atmosphere, can be thought of as the glass of a greenhouse, although, like many models, this is not a very accurate representation of the natural phenomenon. GHGs have the ability to absorb and radiate infrared radiation (heat). When such gases are present, they keep the atmosphere near Earth's surface warm by absorbing heat from the warmed surface and re-radiating it in all directions, including back down towards the surface. In addition to carbon dioxide and water vapour, methane and nitrogen oxides also contribute to Earth's greenhouse effect, but to a lesser extent.

Climate experts at the International Panel on Climate Change (IPCC) have confirmed that Earth is undergoing global warming because of an enhanced greenhouse effect, also known as the runaway greenhouse effect. Increasing levels of some of the main greenhouse gases (as a result of human activities, such as burning fossil fuels) are causing the atmosphere to retain more and more heat. There will be more about how this works later.

Different gases, different impacts

Different gases in the atmosphere have different impacts on the greenhouse effect on Earth. There are two main factors that determine how much of an influence a gas will have on the greenhouse effect:

- the ability of the gas to absorb long-wave radiation (heat)
- the concentration of that gas in the atmosphere.

Methane, for example, actually has a much greater potential to warm the planet than carbon dioxide, but methane has a relatively short lifetime in the atmosphere: approximately 12 years. Carbon dioxide has an estimated lifetime of 50–200 years in the atmosphere. This is because methane can be broken down into other molecules, whereas carbon dioxide is not very reactive and so can stay in the atmosphere for much longer.

Studies of increases in carbon dioxide and methane gases over time have revealed that carbon dioxide concentrations have increased by approximately 40% since 1750, while methane concentrations have increased by more than 150% in the same time period. However, methane concentrations in Earth's atmosphere are about 1700 p.p.b. (parts per billion) whereas carbon dioxide concentrations are about 400 p.p.m. (parts per million), meaning that the concentration of carbon dioxide is more than 200 times greater than that of methane.

This huge difference is the main reason why environmental groups and government policy makers are much more interested in carbon dioxide concentrations than methane concentrations, although both need to be taken into account in discussions about global climate change. Nitrogen oxides represent just over 320 p.p.b., so they are about a fifth the concentration of methane and, even though they have a global warming potential more than 100 times that of carbon dioxide, their concentration in the atmosphere is more than 1000 times smaller than carbon dioxide concentrations, so they are less of a concern.

Governments all over the world have been looking at various possibilities for preventing climate change from getting worse. Over the years, efforts such as the Rio Summits in 1992 and 2012, and the Kyoto Protocol in 1997, have tried to establish goals for carbon emissions. More recently, ideas of a 'carbon tax' or 'cap and trade' policies have been put forward, so that countries compensate for their excessive carbon emissions. Fast-growing economies such as China and India have been under scrutiny for their exponential increases in energy needs, and have been criticized by industrialized nations for using non-renewable energy sources such as coal, which produce excessive carbon dioxide emissions. It can be considered curious that industrialized countries that for centuries have built their economies on carbon dioxide-emitting fossil fuels would tell countries that are more recently following such economic development that they cannot do the same. It will be interesting to see whether countries all over the world will continue to burn fossil fuels until the last lump of coal or the last drop of crude oil is gone. Then again, perhaps international agreements will curb fossil fuel use and prevent climate change from getting worse.

The warmed Earth emits longer wavelength radiation (heat)

As we have seen with a greenhouse, when sunlight touches an object inside, some of the light energy is absorbed and converted into heat energy, also known as long-wave infrared radiation. On Earth, the mountains, forests, rivers, and oceans absorb some of the sunlight and are warmed. Most of the sunlight bounces off the surface and goes back into space. This is what makes photos such as the one at the top of page 204 possible. Only a small amount is converted into infrared to warm up the surface.

The ability of a surface to reflect light is called its albedo. Light-coloured objects, such as ice and white sand, have a high albedo, so very little light is absorbed and such objects do not heat up as much as dark objects such as dark-coloured rocks and black sand. Think about walking barefoot on light-coloured cement on a hot and sunny day, compared with walking barefoot on black asphalt on the same day. Dark-coloured substances such as the asphalt have a low albedo, and absorb lots of light and convert it into heat.

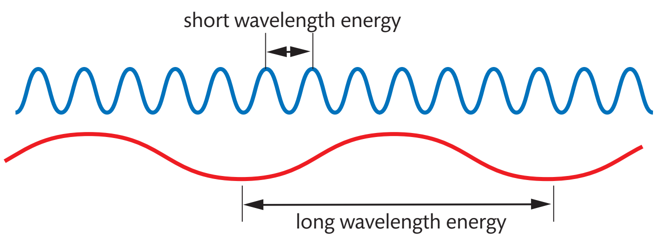

Figure 4.18 Different wavelengths of energy have different properties.

Figure 4.19 A summary of the greenhouse effect: short-wave radiation (shown in yellow) hits the surface and some is converted into long-wave radiation (shown in orange). Some of this infrared heat escapes into space but some (shown in red) is radiated back by greenhouse gases.

How greenhouse gases heat the atmosphere

If Earth had no atmosphere, the heat radiating from low albedo objects on its surface would simply radiate back into space, and at night we would see temperatures plunge to ones similar to the extremely cold temperatures on the Moon.

The reason that this does not happen is because the greenhouse gases absorb and retain the infrared radiation coming from the surface. The greenhouse gases can then re-radiate the heat in all directions, the way a radiator does in a cold room. Some of this heat will be lost to space, but some of the long-wave radiation will be directed down to the surface, keeping it warm. The rest will radiate within the atmosphere, preventing it from getting extremely cold at night when no more sunlight is present. When the Sun rises again in the morning, the surface will heat up and the whole process starts again.

During the winter season, the days are shorter and the angle of sunlight is less direct, so Earth's surface cannot warm up as much. This is why it is colder in the winter. In the summer, days are longer and the sunlight hits Earth's surface more directly and intensely. Earth's surface can get very hot, and, during heat waves, the nights are not cool enough to cause the daytime temperatures to lower.

Fortunately, certain gases in the atmosphere filter out some of the more harmful radiation from the Sun, such as UV radiation. Because the atmosphere filters the sunlight, not all of it reaches the surface. This prevents the surface from getting as hot as the Moon's maximum temperature of +120°C, even on the hottest of summer days. So you can see how the atmosphere acts as a kind of blanket around the planet: at night it keeps the planet warm, and during the day it provides a barrier protecting life from too much solar radiation.

Global climate change is affected by greenhouse gases

Climate refers to the patterns of temperature and precipitation, such as rainfall, that occur over long periods of time. Whereas weather can change from hour to hour, climates usually do not change within a human's lifetime: climate changes generally occur over thousands or millions of years. Climatologists and palaeoclimatologists collect data about atmospheric conditions in recent decades and the distant past, respectively. As thermometers have only been around for a few hundred years, temperatures on Earth from thousands or millions of years ago must be inferred from proxies. (See Nature of Science box on the next page for more about proxies.)

Proxy data show that, in the northern hemisphere 15 000 years ago, it was very cold, and Earth was undergoing a glaciation, or ice age. Ice ages were periods of significant change in climate that produced sheets of ice hundreds of metres thick in regions where today there are thriving cities. For example, in the geographical location that is now Berlin in Germany, there would have been an ice sheet similar to the ones still sitting on Greenland and Antarctica today. The last ice age ended about 10 000 years ago, and we are now in an interglacial period associated with warmer temperatures. It does not take much of a temperature drop to produce a glaciation: it is estimated that the last ice age was caused by a global average temperature reduction of 5°C. By looking at deeper ice cores, we know that there has been a succession of ice ages over millions of years.

Because the greenhouse effect is often misunderstood, be sure to master the scientific vocabulary and concepts. This is challenging for students and adults alike. Few people can explain it precisely, too often saying something incorrect such as 'sunlight is trapped in the air'.

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How can scientists determine a quantitative value for something that is not directly measurable? The answer is by using a proxy, which is a measurement that is used in place of another one. Because it is impossible to go back in time and measure the temperature of the atmosphere 15 000 years ago, climatologists use proxies, such as tree rings, coral reef growth, and the presence of fossils of temperature-sensitive organisms, to estimate the climate back then. By digging in layers of sediment 15 000 years old and looking at the kinds of bones, shells, coral reefs, plant fossils, and even pollen grains, climatologists can work out what the climate was like at that time in the past. Certain species of foraminifera microfossils, for example, can reveal temperature changes via slight changes in the chemical compositions of their shells.

An ice core being removed from the drilling apparatus.

Layers found in thick sheets of ice that have been formed by annual snowfall can also be used in a similar way as tree rings and ocean sediments. By drilling into the ice and taking cylinder-shaped samples, called ice cores, scientists can study the substances trapped in the layers, such as air bubbles from the year when the layer was deposited. Researchers at Vostok Station in Antarctica have collected layers of ice from more than 3000 m down, yielding climate information going back more than 400 000 years. One indication of temperature is the frequency of different types of isotopes (versions of atoms) found in the air bubbles. Oxygen atoms, for example, are usually found in their most abundant isotope, which is oxygen-16, but can also be found in their 'heavier' form, oxygen-18, which has a greater mass because it has two extra neutrons. When glaciations happen, the oceans have a slightly higher ratio of oxygen-18, and the glaciers that form have a slightly higher ratio of oxygen-16. By examining these ratios in ice and in the shells of marine fossils, climatologists can trace the colder and warmer periods of the past.

CHALLENGE YOURSELF

5 The graph below shows the results of collecting data representing thousands of years trapped in ice core samples.

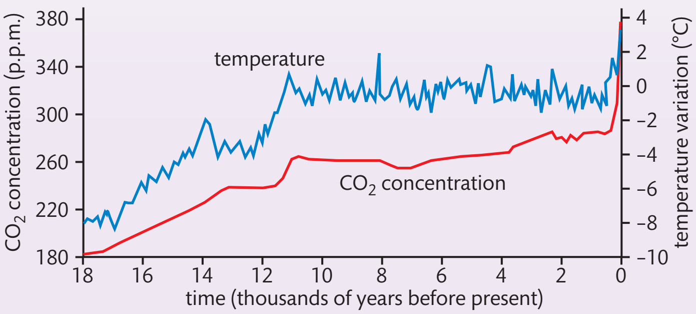


Figure 4.20 Ice core data.

The red line on the graph shows carbon dioxide concentrations that were measured from air bubbles trapped in the ice.

The blue line shows fluctuations between warmer temperatures that are close to zero (representing no change from modern climatic conditions) and colder temperatures several degrees below what they are today.

(a) Is there a strong or a weak correlation between carbon dioxide levels and atmospheric temperatures over the last 400 000 years?

(b) Can scientists conclude that there is causality from this graph: that rising carbon dioxide levels cause global temperatures to go up?

(c) What further evidence would be necessary to confirm or refute causality?

Earth has shown many fluctuations in global temperatures over millions of years. Such fluctuations happened long before humans started producing excessive greenhouse gases. The changes being observed now are alarming scientists because they are happening so quickly and cannot be explained by natural phenomena.

Many factors are thought to contribute to global temperature changes over time, for example volcanic activity and particles suspended in the air, the quantity of radiation from the Sun, the position of the continents (which move on plates over millions of years), oscillations in ocean currents, fluctuations in Earth's orbit and the inclination of its axis, and probably other phenomena that are yet to be discovered. However, in this chapter we are only going to focus on the influence of changes in the composition of the atmosphere, notably the presence of greenhouse gases.

As shown in Figure 4.20, there appears to be a strong correlation between temperature increase and carbon dioxide increase. Knowing the properties of greenhouse gases, as discussed earlier, it is clear that an increase in carbon dioxide levels will lead to warming of the atmosphere, because it would increase the greenhouse effect. Having said this, closer inspection of the data shows that the increase in temperature (in blue) happens first and then the carbon dioxide concentration (in red) rises. This lag time is partly explained by the fact that, as oceans warm up, they release carbon dioxide, because gases dissolve less well in warm water than in cold water. A positive feedback loop leads to further increases in temperatures over time: warmer temperatures → more carbon dioxide → even warmer temperatures → even more carbon dioxide, and so on.

NATURE OF SCIENCE

Want to see the data for yourself? One of the principles of science, especially research funded by taxpayers, is to make data available to the public. This is to allow verification, critique, and sharing of data, so that scientists with many different approaches can combine their findings and advance our understanding of the topics being studied.

One organization that does this is NOAA. If you go to the NOAA Earth System Research Laboratory Global Monitoring Division's website (see the hotlinks at the end of this section), you will find maps, graphs, and databases of measurements of carbon dioxide and other atmospheric gases over many decades. Check out the section called Products.

TOK

How do scientists know that the current situation is exceptional, that the changes in Earth's atmosphere are being caused by human activities and are not just part of a natural phenomenon?

The industrial revolution

Ever since machines started replacing hand tools in Europe in the 1800s, humans have produced increasing quantities of carbon dioxide from factories, transport, and other processes using fossil fuels, notably coal and oil. In addition, burning forests to make way for farmland and burning wood for cooking and heating has contributed to this increase.

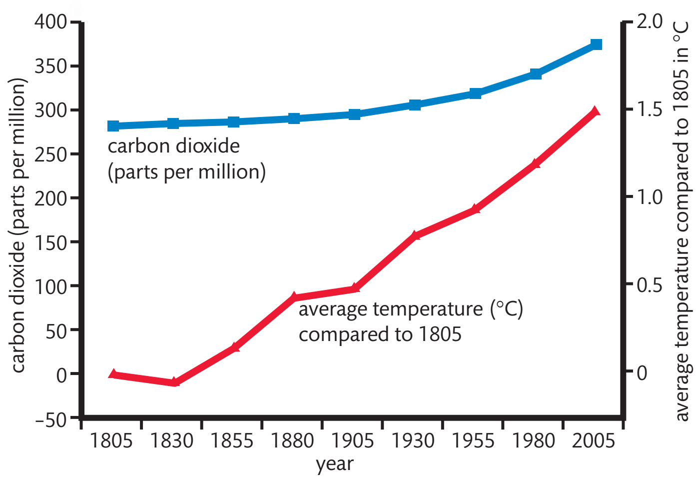


Figure 4.21 Two hundred years of atmospheric changes.

Over the decades, human activities have produced enough carbon dioxide to considerably raise the percentage of this gas in the planet's atmosphere. Estimates suggest that the level of carbon dioxide in the atmosphere has increased by more than 35% compared with its pre-industrial revolution levels.

Recent increases in atmospheric carbon dioxide are largely due to increases in the combustion of fossilized organic matter

The gases produced by human activity that retain the most heat are among the ones we have already identified as greenhouse gases: carbon dioxide, methane, and oxides of nitrogen. The concentrations of these gases in the atmosphere are naturally low, which normally prevents too much heat retention.

The number one source of carbon emissions as a result of human activity is transport that is based on fossil fuels: cars, lorries, diesel trains and airplanes. Other human activities that put carbon dioxide into the air include the following: deforestation, heating homes by burning fossil fuels, maintaining a diet high in meat (the meat industry is highly dependent on fossil fuels), purchasing goods that have to be transported long distances from where they are produced to where they will be used, travelling long distances between work and home, purchasing foods that are grown out of season in greenhouses heated by fossil fuels.

Each vehicle produces its own mass in carbon dioxide every year.

Human activities contribute to the production of other greenhouse gases. Again, diet has an impact here, this time with the production of methane. Remember that methane is produced by anaerobic microorganisms present in the guts of animals. Mass consumption of meat, especially in the USA, where people eat the most meat per person per year, has led to an increase in the number of cattle being raised. Cattle are responsible for producing large amounts of methane that escape into the atmosphere.

Lastly, oxides of nitrogen (NO_x) are produced by human activities such as:

- burning fossil fuels (e.g. gasoline in cars) and using catalytic converters in exhaust systems
- using organic and commercial fertilizers to help crops grow better
- industrial processes (e.g. the production of nitric acid).

Consumer demands push industries to produce more, which means burning more energy and releasing increasing amounts of greenhouse gases.

Consumer demands for wood products such as housing, firewood, furniture and paper lead to massive deforestation.

The problem is that human production of greenhouse gases shows little sign of slowing. As consumer demands for fuel and food increase, so the excess production of waste gases increases.

Do not confuse the greenhouse effect with the depletion of ozone. Although both are the result of human activity, and both influence the atmosphere, they are not interchangeable phenomena. They have different causes and different effects on the environment.

NATURE OF SCIENCE

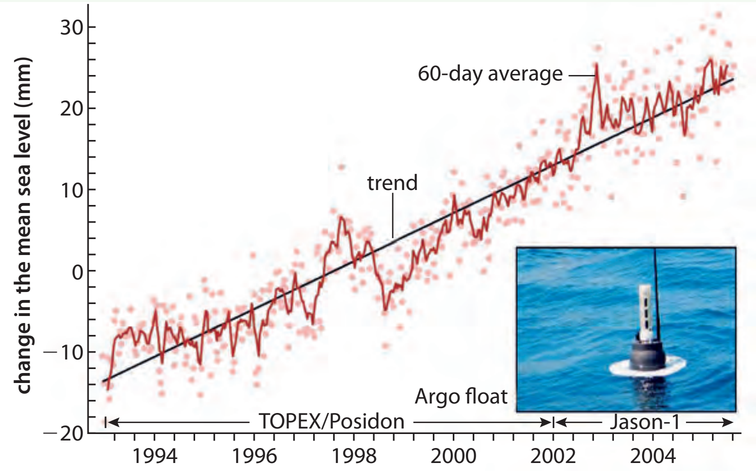
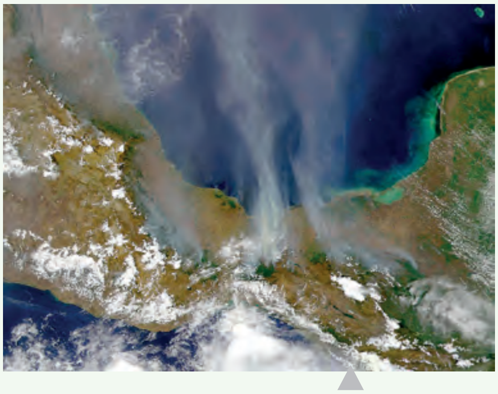


Figure 4.22 NASA data on sea level and the Argo marker, which is used to make the measurements.

How do scientists collect data to see climate change? Look at the various types of data on this page. What kinds of technology are necessary in order to collect the data? How do these data contribute to our understanding of climate change? Large portions of this chapter have dealt with carbon dioxide concentrations: how and where are they collected? Do stations in different parts of the world agree or disagree about trends in carbon dioxide emissions?



This is a satellite photo of forest fires in the Yucatan peninsula in 1998. The forests were drier than usual that year. Forest fires release large quantities of carbon dioxide into the atmosphere.

Threats to coral reefs

The organisms that build coral reefs are very sensitive to the following: water temperature, water acidity, and the depth of the water. Unfortunately, all three factors are changing in the oceans of the world as a result of human activities. Increased carbon dioxide concentrations in the air lead to increased dissolved carbon dioxide in the oceans, which lowers the pH of seawater. When it is intense, ocean acidification leads to the death of coral polyps and algae, and when they die the reefs are not built up anymore. As a result, the colour of the reef goes from being richly multi-coloured to being as white as bone. This coral reef death is called bleaching and it interrupts the food chain, causing many of the organisms that live there to seek food and shelter elsewhere. Similar to a forest that has lost all its leaves because of acid rain, a bleached coral reef can no longer support the rich ecosystem that once lived there.

Are humans causing climate change?

Not everyone is convinced that climate change is happening, or that it is caused by human activity. Such critics are sometimes referred to as 'climate change deniers', and they have a number of criticisms about the IPCC's findings.

How do scientists respond to such criticism? What arguments and justifications do they use in response? Table 4.5 presents a few.

Table 4.5 Opinions of climatologists and their critics

Challenges from critics	Possible responses from climatologists
Climate change as a result of human activity is just a theory, not a fact.	Evidence clearly shows temperature increases since the industrial revolution. Decades-old predictions of extreme weather events, record temperatures, and receding glaciers are being confirmed day after day. Climate change is not a debate or a controversy: it is well-supported by an increasing volume of data. The findings of the IPCC state, 'The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO_2 since 1750.' The term 'radiative forcing' means the difference between the energy arriving at the surface and the energy being lost into space. And the increase in CO_2 referred to is clearly traced to human activity.
There is disagreement within the scientific community about human-induced climate change. Many scientists disagree and have published research showing that climate change is not due to human activity.	The vast majority of recent publications from climatologists confirm anthropogenic climate change; there is a consensus in the scientific community. Often the dissenting scientists who are quoted by critics are not climatologists, or they are quoting out-of-date or refuted data. In other instances, scientists only disagree on the quantity of change or on the amount of responsibility of human activity.

Challenges from critics	Possible responses from climatologists
Your models predicted even more of a temperature increase than is actually happening. How can you explain that? Human activities such as burning fossil fuels are increasing, so why aren't the temperatures increasing equally fast?	Like any science, climatology is complex and we are learning new things all the time. For example, human activities such as transport produce particles in the air that remain in suspension, and some of these aerosols can diffuse sunlight, causing a reduction in the amount of short-wave solar radiation reaching the surface. Less solar radiation hitting Earth means lower temperatures because there are fewer rays of short-wave radiation reaching the surface to be converted into infrared. This phenomenon is cancelling out some of the predicted warming.
There have been huge fluctuations in climate in the past, and the current changes that we are seeing in recent decades are natural. For example, the Sun is currently in a phase of high-energy output. Wouldn't that be a more logical explanation?	Although it is true that Earth's climate has seen warming and cooling in the past, those changes were relatively slow, taking place over thousands or millions of years. The changes that we are seeing now are happening on a scale of decades, and the speed and magnitude at which CO_2 levels and temperature are increasing are unprecedented. One concrete example of the consequences are so-called 100-year storms that, instead of happening once every century, are occurring several times within the same decade. As for the Sun's output: yes, it is currently in a high-output phase, but that extra energy has only a small fraction of the effect that human-induced global warming has. Also, the most recent hottest years on record happened during a period of lower solar output.
Insisting that climate change is caused by human activity means that, to solve the problem, we are going to need to reduce CO_2 emissions. That will have a severe negative economic effect, as many carbon-based industries will lose revenue.	The alternative, if we let people introduce more and more greenhouse gases into the atmosphere, will exacerbate the already highly destructive patterns we are seeing, and the cost of fixing these new problems is difficult to imagine. Enormous economic burdens are presented by problems such as the damage caused by an increase in extreme weather events, such as super storms and hurricanes, rising sea levels, droughts as well as flooding, a reduction of snow at high altitudes influencing melt water supplies downstream, to name a few.

In the end, climatologists make a clear distinction between what is politically controversial and what is scientifically controversial. The political debate is often driven by non-scientific arguments. One way to spot non-scientific arguments is to look for whether or not the proponent's comments are motivated by economic arguments, notably when they are motivated by their affiliation with industries that produce large quantities of carbon dioxide. As such industries would potentially lose revenue if limits were put on carbon dioxide emissions, it is in their interest to promote doubt and controversy.

NATURE OF SCIENCE

Climate change raises many issues about how science works. Here are four to consider.

1. The fact that there are sceptics and critics of the IPCC reports on global climate change is a good thing. Science encourages constructive criticism and verification, and is open to modification if the criticisms are valid. Often errors and misinterpretations of data are spotted when many people read a publication, and this pushes scientists to be more precise and to be better communicators.
2. The IPCC report is filled with qualifying statements such as 'likely', 'highly likely', 'extremely likely' about the future. Why can't IPCC just make up its mind and say that something is sure to happen? Because systems such as global climate are complex, scientists do not fully understand how they work and, although they are regularly gaining further insights, sometimes they are wrong. For example, the predictions of how fast global temperatures will increase seem to have been confirmed for some years but not for others.
3. Climate change deniers will grab onto such inaccurate predictions and say, 'See? Your models are wrong. Therefore, no one should listen to you.' This is an example of cherry picking, something both sides of the debate are accused of doing. Cherry picking is a form of confirmation bias that consists of only looking at the evidence supporting your side of the argument, and ignoring or downplaying the evidence that hurts your argument. Both sides of the debate have been accused of following blind faith rather than objectively assessing the evidence.
4. Scientists need money for their work, and they often get that money from grants offered by governments and industries. If a scientist is getting funding from an organization that promotes the preservation of nature, the chances are reasonably good that that scientist will tend to look for evidence of human-induced climate change, whereas a scientist whose funding comes from industries highly reliant on fossil fuels will probably tend to look for evidence against human-induced climate change. Journalists and citizens need to be vigilant about this, and double-check where the interpretations of the data are coming from.

CHALLENGE YOURSELF

6 Do you know your carbon footprint? This is the amount of carbon dioxide you as an individual are contributing to the atmosphere. There are many online 'Footprint calculators' available, notably from the Nature Conservancy and WWF. Use the hotlinks at the end of this section to try one: what do you get, and how do you compare with the rest of the world? In what ways are you willing to try to reduce your carbon footprint: diet, transport, home energy use? The website that calculates commuters' itineraries on the Metro system in Paris, France, also calculates how much carbon is saved by not burning fossil fuels for the same commute. Does your public transport system's website have a similar calculator?

Too often people think that climate change is someone else's doing, that their personal day-to-day decisions do not have an impact.

TOK

When playing a board game with family or friends, cheating is frowned upon. If one player took more turns or more points than the rules allowed, that person would be considered a cheater and might be asked to leave the table. If everyone around the table started cheating, the game would break down completely. Are there similar situations in society? For example, if a few people break the law, they are often treated as criminals and punished; but if everyone cheated all the time, society would break down. Are there any parallels with pollution? If people are knowingly polluting and not doing anything to reduce their carbon footprint, are they treated by society as cheaters? There are enough warning signs to lead experts to invoke the precautionary principle. This is an ethical theory that says that action should be taken to prevent harm even if there is not sufficient data to prove that the activity will have severe negative consequences. It also stipulates that if people wish to engage in an activity that may cause changes in the environment, they must first prove that it will not do harm.

Without the precautionary principle, industries and consumers tend to proceed with their activities until it becomes clear that harm is being done to the environment. When irrefutable proof is provided, usually action is taken to reduce the activity in question. For example, the use of the pesticide DDT was prohibited in North America when it was proven to accumulate in ecosystems and reduce populations of birds of prey such as the bald eagle. That decision saved the bald eagle from extinction. How can we 'prove' that something is safe for the environment?

With regards to global warming, tenets of the precautionary principle say that preventative action should be taken now to reduce carbon emissions and greenhouse gas production before it is too late. In addition, the principle holds that those who wish to continue producing excess greenhouse gases should prove that there are no harmful effects before continuing.

In response, farmers, manufacturers, and transport providers, among others, wonder why they should invest money in new techniques that reduce greenhouse gases if scientists are not 100% sure how an enhanced greenhouse effect is going to be harmful to the environment. Industries that make the effort to invest in such measures may find themselves less economically viable than their polluting competitors.

Consequently, unless preventative measures are taken across the board by countries worldwide, there will always be polluting competitors who can offer products at a lower price. The risk is that they will drive the ecologically conscious companies out of business because they do not use any of their capital on ecological measures.

Ideally, well-informed consumers could choose products or services that are provided by ecologically minded companies. If this is done on a massive scale, companies would provide eco-friendly products and services to attract customers, and those companies that did not would be shunned as rogue companies by consumers and be driven out of business.

To learn more about NOAA and carbon footprints, go to the hotlinks site, search for the title or ISBN, and click on Chapter 4: Section 4.4.

Exercises

10 Distinguish between how a garden greenhouse works and how the greenhouse effect on Earth works.

11 Of the greenhouse gases discussed in this chapter, state which one has a warming potential approximately 100 times that of carbon dioxide. Why aren't scientists talking more about this if it has such a potential to increase the greenhouse effect?

12 In what ways could you reduce your consumption of fossil fuels on a day-to-day basis?

13 A scuba diver returns to her favourite coral reef only to find it empty of life and all the corals turned white. She asks you if you know what this phenomenon is: what do you tell her?

Practice questions

1 What is a community?

A A group of producers and consumers living and interacting in an area.

B A group of species living and interacting in an area.

C A group of organisms living and interacting in an area.

D A group of populations living and interacting in an area. *(Total 1 mark)*

2 The scarlet cup fungus, *Sarcoscypha coccinea*, obtains its nutrition from decaying wood by releasing digestive enzymes into the wood and absorbing the digested products. Which of the following terms describe(s) the fungus?

I. Autotroph

II. Heterotroph

III. Saprotroph

A III only.

B II and III only.

C I and III only.

D I, II, and III. *(Total 1 mark)*

3 Why do food chains in an ecosystem rarely contain more than five organisms?

A Nutrients are recycled by the decomposers back to the producers.

B Nutrients are lost from the ecosystem when organisms die.

C The conversion of food into growth by an organism is not very efficient.

D Energy is recycled by the decomposers back to the producers. *(Total 1 mark)*

4 Several greenhouse gases occur in the atmosphere. Carbon dioxide (CO_2) is one of them but so are methane (CH_4) and oxides of nitrogen (NO_x). Why are oxides of nitrogen classed as greenhouse gases?

A They trap some of the long-wave radiation emitted by Earth's surface.

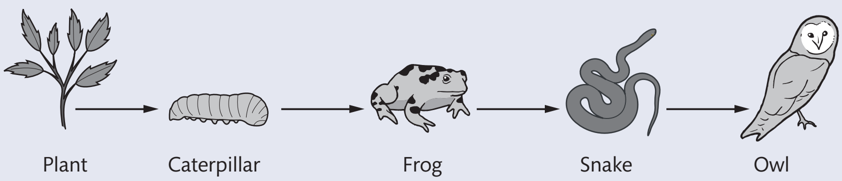
B They prevent short-wave radiation from reaching Earth's surface.

C They dissolve in rainwater to produce acid rain.

D They are only produced by human activity whereas CO_2 and CH_4 are also produced naturally. *(Total 1 mark)*

5 Explain the shape of the pyramids of energy that are constructed by ecologists to represent energy flow in an ecosystem. *(Total 3 marks)*

6 This diagram represents a simple food chain. In which ways is energy lost between the trophic levels?



I. Heat loss through cell respiration.

II. Material not consumed.

III. Material not assimilated.

A I and II only.

B I and III only.

C II and III only.

D I, II, and III. *(Total 1 mark)*

7 Describe the relationship between the rise in the concentration of atmospheric carbon dioxide and the enhanced greenhouse effect. *(Total 5 marks)*

8 Outline the precautionary principle. *(Total 2 marks)*